

DRY TAILINGS DISPOSAL FROM OIL SANDS MINING

Volume 1 and 2

DRY TAILINGS DISPOSAL FROM OIL SANDS MINING

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For: Environmental Protection Service
Environment Canada

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As will be familiar to many readers of this report, development of novel processes is a slow, expensive and perhaps frustrating experience for many involved. With completion of the laboratory and computer work presented in this report, the first step for "infant" "Dry" Tailings Disposal (DTD) technology, has been taken. At least two further steps of continuous test work are needed before the technology could be useable in a commercial environment.

While there are no firm promises that any of those who have been involved in this work to date will continue to support us in future, we are very grateful for their help so far. We hope you find the results as encouraging as we do.

Thank you everyone!

EXECUTIVE SUMMARY

The accumulation of non-trafficable sludge and toxic water from the oil sands plants may pose a problem for generations to come. Although the sludge or "slimes" problem is characteristic of tailings disposal operations for most mines around the world, the tailings ponds in the oil sands industry are the largest and probably the least acceptable environmentally of any mining industry. Other mining industries, such as the uranium mining industry, produce toxic waste substances which are disposed of in tailings operations. But the oil sands operations produce highly toxic waste water (LC₅₀ to rainbow trout of 4%). The presence of bitumen slicks on the ponds has also necessitated elaborate bird deterrents for migrating water fowl.

Numerous government agencies, Syncrude, Suncor, and other potential operators have conducted extensive research into alternative tailings disposal measures. Perhaps \$15,000,000 has been spent in total. While several technically interesting schemes for sludge treatment have been identified, few of these appear to be attractive on a commercial scale or offer the potential for a trafficable solid waste which can be revegetated.

The report which follows reviews background data regarding the properties of the oil sand, the nature of the mining, processing and tailings disposal operations, and the characteristics of the clays which have contributed to the difficulty inherent in sludge disposal operations in Volume I, sections 1.0 to 6.0.

Background knowledge in these areas, along with several ideas and previous work on the potential for whole tailings treatment have led to the concept of chemically coagulating and settling the whole tailings and attempting to work with the deposited soil as an engineering material.

Volume II, sections 7.0 to 15.0 of this report, discusses our tests and evaluation of the technical and economic feasibility of a chemical treatment of whole tailings. Figure ES.1 is a photograph of the material as deposited in one of the geotechnical "flume" tests, while Figure ES.2 illustrates schematically how the material might be handled commercially.

Investigation of the effect of chemicals on settling and consolidation of whole tailings has led us to choose an optimum dosage of 900mg/l of calcium oxide (CaO) and 8mg/l of a polymeric coagulant aid, Cyanamid A-110, as the optimum chemical mix. Probably due to the ability of the polymer to align clays in an "edge flocculated" state, the chemical mix is able to achieve high density and relatively high permeabilities simultaneous. In some cases, we have achieved a density comparable to the in-situ density of oil sands. Even at these high densities, the material

(E S - 2)

has a relatively good permeability, equivalent to beach material, of approximately 5×10^{-5} cm/sec.

Laboratory observations of the rate of drainage and drying suggests the material might dry in the field within about a week to be suitable to support construction heavy equipment.

The major implication to extraction process water recycle is that a bleed stream of perhaps 15% of the total water consumption might be needed in the final years of the project. This bleed stream could also serve as a permanent treatment and disposal of the accumulated toxic water by continuing to operate after the plant has shut down.

The use of lime in this process does appear to contribute a potentially significant shear strength increase to the treated tailings after the tailings have dried out. While the material remains wet there is little if any strength contributed by the apparent carbonation stabilization mechanism.

The most significant factor for conceptual tailings disposal system design is that the material should be disposed of through a "central discharge" configuration, illustrated in Figure ES.2, or a system similar to it.

In the investigation of the economics it was determined that the most significant consideration is the reduction of the bulking factor achieved with whole tailings treatment. Material handling costs are essentially volume dependent, and current disposal operations involve a bulking factor of 1.4 over that of the oil sand in-situ. Treatment with lime and polymer achieves a bulking factor which, in the best case was essentially 1.00, but perhaps averaging 1.10 and is thus significantly less expensive than current disposal technology. While it is very premature to judge commercial economics based on laboratory scale testing, a potential reduction in costs might be of the order of 20 or 25% over that for conventional disposal technology.

Further test work is needed and a proposed program for pilot scale testing is outlined.

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Figure ES.1

Flume Test Apparatus Showing "Disposed" "Dry" Tailings

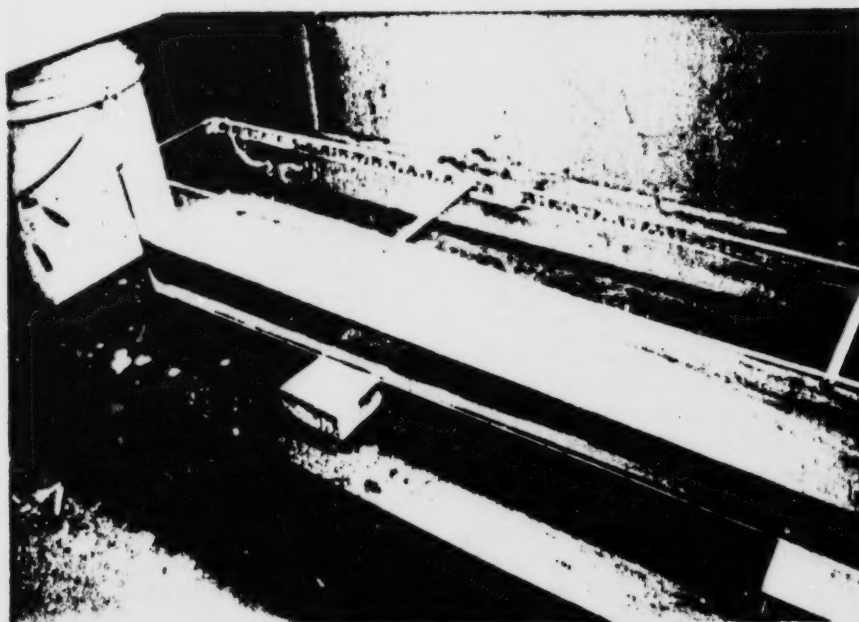
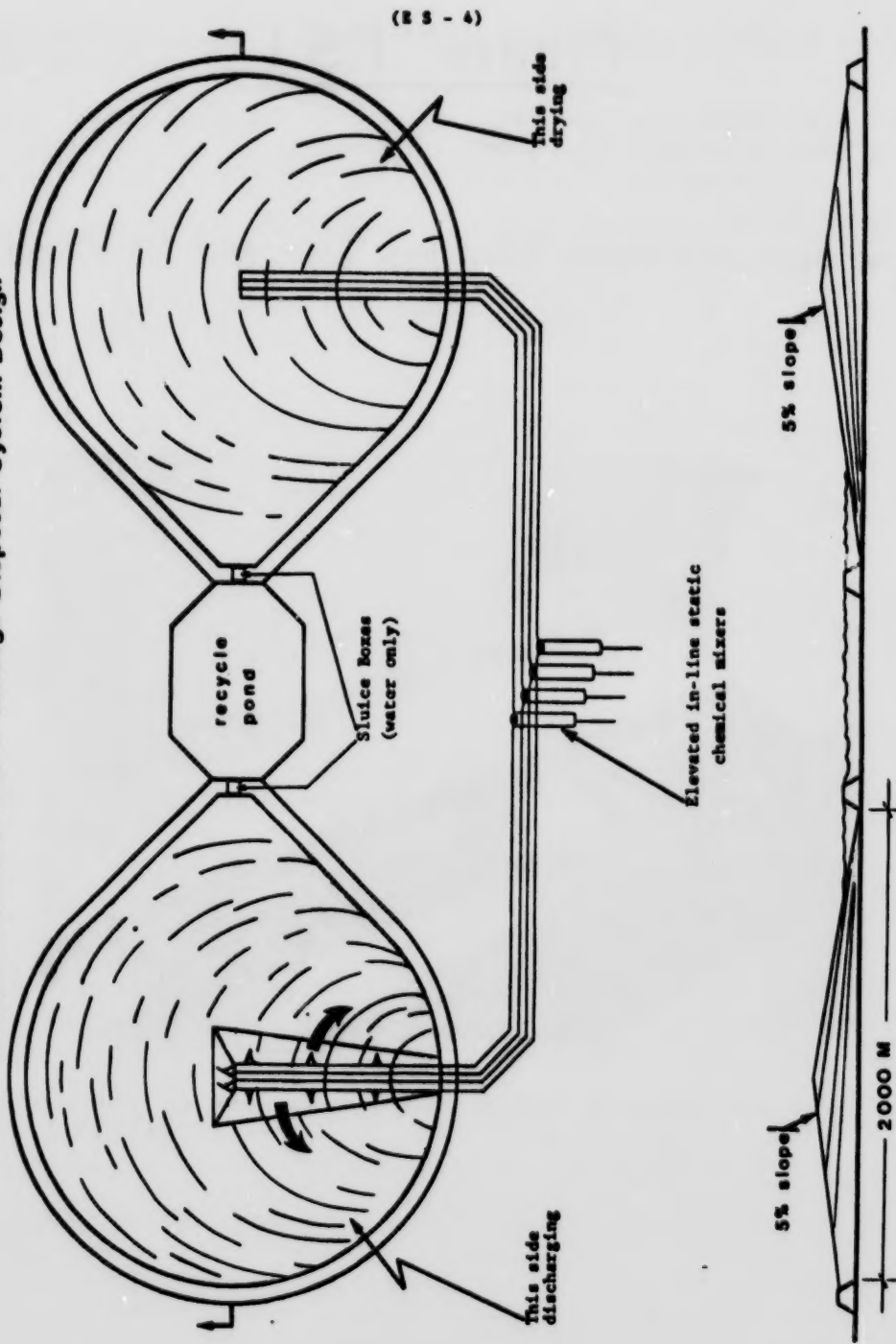


Figure ES.2

Potential Treated Whole Tailings Disposal System Design



1.0 INTRODUCTION

Commercial exploitation of mineable oil sands in the Athabasca region of northern Alberta, has depended on an efficient, inexpensive means of separating the bitumen from the sand.

Although the Cree Indians likely discovered centuries ago that partial separation was possible by immersing oil sands in water, this new energy resource lay dormant until the early 1900's.

By then, several different entrepreneurs and government researchers had begun experimenting and operating small plants with various techniques of "washing" the oil from the sand with hot water. While the hot water process worked reasonably well for high-grade oil sands, oil sand which contained significant amounts of clay fines tended to emulsify rather than wash bitumen free.

Development of the current variation of the hot water process, which could extract bitumen from an oil sand containing significant amounts of clay fines was to await the basic research of Dr. Karl Clark. Beginning with the earliest days of the Alberta Research Council in the 1920's, Dr. Clark investigated the use of caustic additives that dispersed the troublesome fine clays and made the process workable for oil sand containing significant amounts of clay.

Clark's "cure" for the problem of clay fines, the use of sodium hydroxide as a clay dispersant, was also known to have a serious "side-effect", making it much more difficult to remove the clay fines from the wastewater effluent of the hot water process. The long, slow settling and poor compaction of clay sludge in the retention pond(s) has come to be known as the "pond water problem" or the "sludge problem." The nature of the problem can be appreciated by viewing Figure 1.1, "whole" tailings which has been settling for 3 months.

There were no really good indications of how significant this problem would be on a larger scale, prior to the start up of the commercial operation of the Suncor plant on September 25, 1967. Tailings sludge was soon discovered to be settling even slower and compacting to an even lower density than had been anticipated from pilot tests. In some cases, less than 30% solids was being obtained by ponding and settling. What was previously thought to be mainly a process water recycle problem was proving to be a serious and permanent environmental hazard. Camp, 1976 provides a comprehensive description of the extraction and tailings disposal technology.

Tailings ponds in the mining industry are usually a blight on the landscape, at least while the plants are operating. Oil sands tailings ponds are easily the worst. Due to the scale of

1.2

operations, they are larger in area and in volume than typical tailings ponds. Oil slicks on the pond surface also cause problems with migrating waterfowl. The water is so toxic to fish that 4% of pond water mixed with fresh water will kill 50% of exposed rainbow trout in 96 hours (MacKinnon, 1981).

With the current level of technology for oil sands operations, there is considerable doubt as to how tailings ponds sludge would be reclaimed, unlike a number of other tailings ponds in various mining industries which have succeeded in solving the problem at least after the plant closes down.

There is no profit in tailings disposal. The competitive nature of mining worldwide and the especially critical cost concerns of the oil sands industry have led to the implementation of "hydraulic" tailings disposal methods. This type of tailings disposal operation is believed by many in the mining industry to be the most economic method and therefore an unavoidable part of mining operations. It involves the use of coarse material from the solid waste (the bottom sand material in Figure 1.1) to construct hydraulic tailings dykes which are used to contain the slimes or sludge portion of the solids. The sludge is then allowed to settle for a long period of time (effectively more than a year) to remove as much of the slow-settling solids as possible from the water being reclaimed. Almost all mining operations reuse as much water as possible and require clarification ponds for maximum recycle water quality, i.e. minimum solids content.

The solutions which have been developed in other mining operations, have usually been the product of extensive research, conducted and financed by industry and/or government agencies. These solutions are usually more expensive than "conventional" disposal methods.

The end of mining operations represents a different problem. Once the plant ceases operation, the tailings pond, including the sludge, one way or another, must become a part of nature again, with or without man's help.

Unfortunately, the consequences of nature's reabsorption of a tailings pond without human intervention can be hazardous to all life in the vicinity of the tailings pond should a catastrophic failure of a tailings dyke occur. Such an event is inevitable due to heavy rainfall or perhaps even a mild earthquake, without virtually perpetual vigilant surveillance and maintenance.

Current environmental guidelines for reclaiming tailings ponds are primarily oriented towards obtaining vegetative cover on the exterior slopes of the tailings dykes to prevent natural erosion and also towards detoxification of the pond water. While developing "trafficable" soil from the sludge may be viewed as desirable, it is currently technically difficult and very costly.

From the earliest evidence that clay fines were difficult to remove from the hot water process effluent, research on sludge treatment, concentrating almost exclusively on methods of separating the slow-settling clay solids from water, has been intensifying. While there have not been any techniques developed for treating clay sludge from the Athabasca oil sand which have been incorporated in the commercial plants, there are several sludge treatment schemes for comparable materials used elsewhere in the world.

Both of the plant operators continue to experiment with reprocessing sludge to recover bitumen and separate water, and Suncor now apparently has a workable method to encapsulate treated sludge in sand using flocculants, currently being tested (Yong, 1982). This method, along with several other processes currently being researched, offers some promise of at least technical viability for reclaiming the large volume of sludge which has already accumulated.

Examples of such processing technology which are used commercially elsewhere in the world are the utilization of sand-sludge layering or "spraying" in the Florida phosphate slimes disposal operations, (Scheiner, 1981) and the use of so-called "chemical fixation" techniques in the processing of bauxite red mud slimes (Moodie, et al, 1975) and uranium mill tailings (Marcus, 1982).

The authors of this report have taken a different approach from the typical methods used to treat sludge. We avoid producing it in the first place, as illustrated in Figure 1.2. We are instead, chemically treating the "whole" or "total" tailings material, the sand and clay together. We have found that a small amount of chemical "glue" when added to the whole tailings is capable of coagulating the clay and sand together and allowing "hindered settling" of a sand-clay mixture. When properly handled, we believe the material can be utilized, including building dykes from it in a similar fashion to current hydraulic dyke construction.

Our concept of "lime coagulation and stabilization" for "dry" tailings disposal is described and analyzed in the report that follows, along with a discussion of the properties of the material which are significant to the proper functioning of the technique.

The format we have used for this report is to build upon published background information and knowledge to provide the theoretical perspective that has lead us toward our preferred configuration. We then provide an overview of our tests and results and discuss the implications on a disposal system design. The economics of several configurations of the process which might be used on a commercial scale, as we currently understand them, are also discussed.

The following sections 2.0, 3.0 and 4.0 discuss significant characteristics of the oil sand resource, the processes used to extract the bitumen and dispose of the waste, and the properties of sand, clay and chemicals which affect our treatment method.

Sections 5.0 and 6.0 review background material for what is generally known about oil sands sludge clay characteristics and lime treatment methods. If a reader is familiar with any or all of the technologies described in sections 1.0 to 6.0, they can appreciate the results of our work without reading this background information.

An overview of our work is presented in 7 chapters, sections 7.0 to 13.0. Section 14.0 presents conclusions and section 15.0 recommendations resulting from the work.

As mentioned, Volumes I and II of this report are an overview; detailed discussion of tests and results is presented in the Appendices.

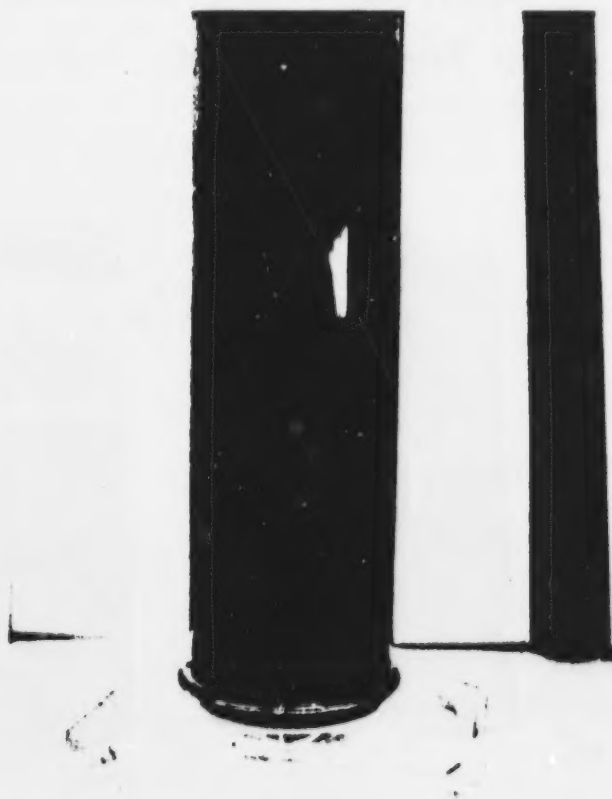
The authors apologize in advance for several known gaps in the test results and interpretation. Although further batch tests would be useful to fill in some of these gaps, we believe it would be more efficacious to obtain such information during larger scale continuous testing.

We hope to get started on such testing soon.

(1.5)

Figure 1.1

Settled Tailings Profile

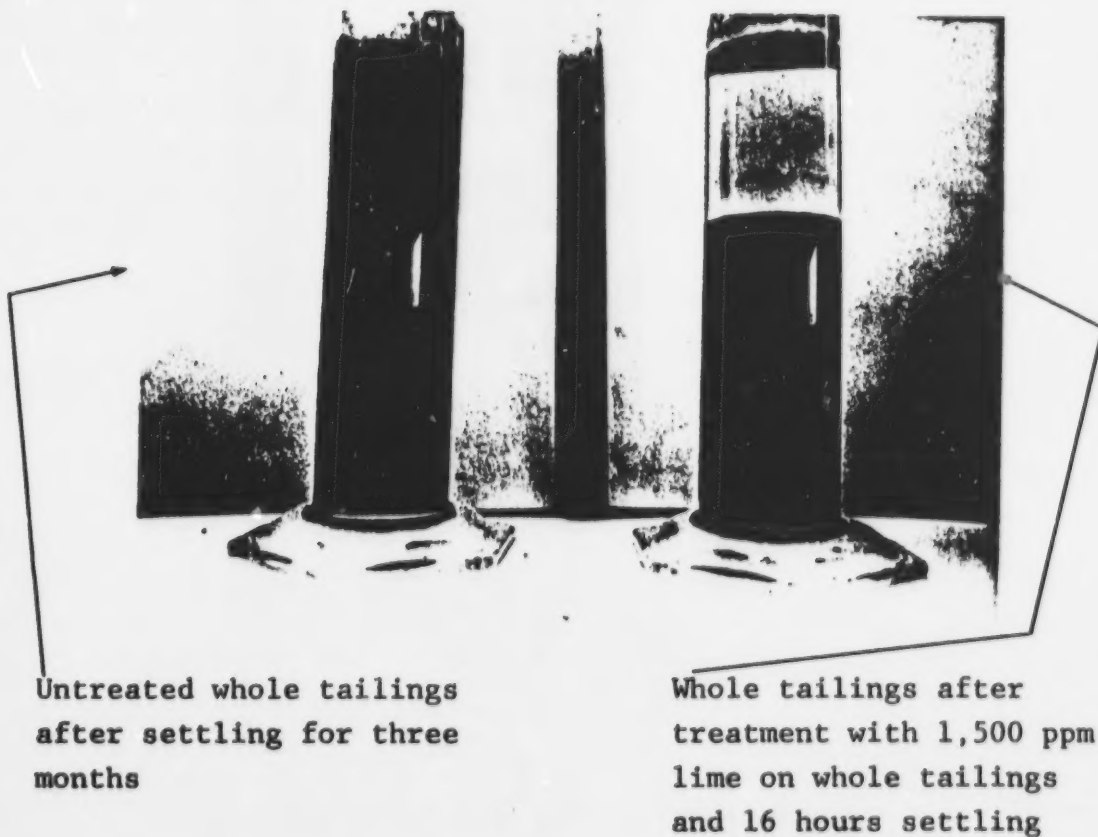


(whole tailings settled for 3 months)

(1.6)

Figure 1.2

Comparison of Untreated and Lime Treated Whole Tailings



2.0 THE NATURE OF MINEABLE OIL SANDS

The oil sand as mined and fed to the processing plants at Syncrude and Suncor would be highly unpredictable in its bitumen and fines content, connate water character and mineral composition were it not for the geological, hydrogeological and mineralogical mapping used for mine control and planning. These sciences provide the means to interpret the characteristics of the undisturbed deposit and, as much as possible, predict the performance of the extraction and tailings disposal operations. This section discusses the principal factors which significantly affect extraction and tailings disposal technologies.

The significance of many of the concerns addressed in this section will probably not be apparent to the reader at this point in a report addressing a novel tailings disposal technology. As will become clearer later, even apparently obscure considerations such as the "oil sand microstructure" have significant implications to many of the properties of the deposit or of tailings such as permeability. When considered in the context of the nature of the in situ deposit, the characteristics of treated whole tailings material will prove to be reasonably predictable from a knowledge of the characteristics of the deposit which are discussed in sections 2.1 to 2.5 which follow.

The reader might prefer to review the discussion of the test results first.

Facies analysis or identification and mapping of oil sand sedimentary structures and depositional history provide the best means of interpreting the oil sand compositional variability. The following section quickly reviews basic McMurray formation oil sands geology, in the Athabasca deposit (the only Canadian oil sand formation/deposit with surface mineable areas).

2.1 Oil Sand Geology

Most of the sediments of the oil sands were originally deposited in a deltaic environment, with extensive fresh water river meanders and sand bars on a salt water ocean. As a result, the mineral and connate water composition of the oil sands, as deposited, was highly variable. Depending on the velocity of the water from which it settled, the sediment may be relatively coarse grained "well-sorted" sand deposited in fast flowing "fluvial channels" or fine silts and clays settled from stagnant water areas such as floodplain marshes. Over time, the finer silt and clay zones tended, to a certain extent, to consolidate to form shales or shaley sands.

Later in geological time, this portion of the continent was

(2.2)

gradually inundated, under the ocean which had been nearby, by the subsidence of all of North America. The resultant erosion and rearrangement of large portions of the sediments by the action of ocean currents makes the interpretation of the depositional environment very difficult and subjective for geologists who study the oil sands. The oil sands are thus characterized by both extreme horizontal and vertical variability.

The porosity and permeability of the sediments also affected the subsequent migration of oil into the formations with the coarser sands (with the highest permeability) becoming virtually saturated with oil and the low porosity shales remaining almost barren.

The preferred way of describing the geological nature of the oil sands is by mapping the ancient river channels, sandbars and beaches, etc., as illustrated in Figure 2.1, a highly simplified schematic of the proposed Alsands mine area. This information, when interpreted simultaneously as a function of depth is typically used to develop stratigraphic cross-sections as illustrated in the simplified schematic of Figure 2.2, which shows some of the major geological characteristics.

The geologist almost never has enough information to be certain of what lies between two adjacent drill-holes. His interpretation is thus always subject to revision as the density of drilling is increased from that used for exploration (perhaps one hole per township, or 36 square miles) to that used for mine grade control (one hole per acre).

Only the latter information is sufficiently accurate to allow reasonable predictability of the grade of ore mined and some ability to deliberately blend the plant feed to minimize the wide variations in bitumen and fines content inherent in the deposit. Even with a very conscientious effort to combine the highest and the lowest grades of processable oilsands with their opposites, to minimize fluctuations in the plant feed grade, changes of several % bitumen or fines still occur. The operating conditions in the extraction plant must be continuously monitored and corrected for such feed quality changes to maintain the highest possible recovery efficiency. As will be seen in sections 3 and 4, these fluctuations also directly effect the quantity and nature of tailings.

2.2 Origin of the Bitumen

There is still considerable uncertainty as to how and where the oil originated although it is reasonably certain that it was initially a "light" oil which flowed fairly readily to where it now rests. One theory is that the oil originated in the Mannville source beds, above the McMurray (now forming mainly Clearwater

shales), and migrated down into the porous and permeable portions of the McMurray formation sands where it was ultimately trapped. The other theory postulates Paleozoic source rocks, below the McMurray, with the oil migrating up to the basal Cretaceous McMurray Formation.

The light oil which originally migrated into the McMurray formation was later subject to water washing and/or biodegradation, both of which resulted in products heavier than the original oil (i.e. having lower API gravity) and increased the sulphur and ash content. The oil was obviously a lot less viscous originally than it is now, as it permeated virtually every porous and permeable area in the reservoir.

The "trapping" mechanisms which determined the ultimate extent of the original oil migration and now of the bitumen bearing sand are still somewhat uncertain. The impermeable Clearwater shales above the McMurray clearly acted as the "cap rock" for the trap, while relatively impermeable limestone generally underlies it. But what determined the lateral migration is unknown, as the sands to the east are at least as porous and permeable as the reservoir sands.

2.3 Microstructure of Oil Sand

Probably the single most characteristic feature of Canadian oil sands, especially compared to most other bituminous sands in other areas of the world, is that the grains are water wet or hydrophilic. The oil in the rock pores is not in direct contact with the mineral grains, each grain is surrounded by a thin film of water (Figure 2.3). Both the water and the oil form essentially continuous phases. This is also quite significant to the hydrogeology of the oil sand which is discussed in section 2.6, to the composition of oil sand connate water, to the interrelationship between bitumen and fines and to the void ratio and bulk density of the sand discussed in section 2.4.

Clay particles are known to adhere directly to the sand grains, but whether or not they protrude through the water envelope is not certain (they are shown in Figure 2.3 as totally within the water phase.) This "attitude" of the clay minerals is also significant to their behaviour in the hot water process which is discussed in section 3, and to tailings treatments discussed in section 8.0. The water envelope or hydrophilic nature of the sand grains is often regarded as the main reason why the hot water process works at all. However, a caustic hot water process will work on oil wet oil sand (such as Utah's) because caustic is capable of altering the sand surface tension from oil to water wet.

(2.4)

2.4 Bitumen / Water / Fines Relationship

Due to the manner in which the light oil (now bitumen) flowed into the formation and also due to the placement of clay particles between the sand grains, the amount of bitumen, water and fines present are interrelated by volume constraints.

The "void" space between coarse sand grains not completely filled by fine clays, in the general orientation suggested in Figure 2.3, leaves space which may be occupied by bitumen or water. As bitumen and water have essentially the same density, the overall weight and density of a unit of volume of oil sand is not affected by the proportions of water or bitumen contained in the oil sand.

Figure 2.4 serves to illustrate several important relationships between the solid and "fluid" contents of oil sand. While the percentage weight of the portion of the oil sand is obviously lower if the solid content is higher, the size distribution of the solids has an effect on the relative amounts of each. Hence the amount of pore fluid (bitumen and water) is inversely correlated to the percentage of solids which can also occupy pore spaces (i.e. the % - 325 on the X-axis of Figure 2.4), as illustrated in Figure 2.4.

While this correlation is obviously an approximation, it is well known that the bitumen content of oil sands is generally lower at higher fines levels. Figure 2.4 can be used for many practical purposes with considerable confidence.

2.5 Oil Sands Mineralogy

High grade oil-bearing sands in Athabasca are predominantly very fine - to fine-grained ($62.5 \mu\text{m}$ - $250 \mu\text{m}$), although coarser sands and conglomerates are known. Shale beds within the oil sands consist of clay and silt-sized material. Typical Athabasca oil sands consists of 95% quartz sand grains, 2-3% feldspar grains and 2-3% mica and clay minerals.

Feldspars are composed of:

KAlSi_3O_8 -orthoclase, and $(\text{Na,Ca})(\text{Al,Si})\text{AlSi}_2\text{O}_8$ -plagioclase.

The micas are mostly:

$\text{K}_2\text{Al}_4\text{Si}_6\text{Al}_2\text{O}_{20}(\text{OH,F})_4$ -muscovite, and minor biotite

$(\text{HK})_2(\text{Mg,Fe})_2\text{Al}_2(\text{SiO}_4)_3$, (<1%) which are easily distinguishable by microscope when they are present, as they have a thin flake shape. The clay minerals which are present are largely

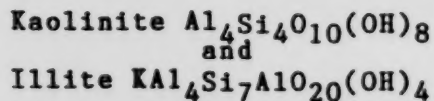
(2.5)

weathering products of the micas.

The oil sand also contains trace amounts of heavy minerals such as zircon (containing zirconium) and illmenite (containing titanium). These may prove significant to tailings treatment technology in future as they are concentrated by the hot water separation process in the froth and could be recovered from the dilution centrifuging tailings.

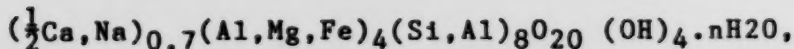
Carbonates such as CaCO_3 -calcite, and FeCO_3 -siderite are also present in small amounts as local cements.

Clay minerals, as discussed earlier, occur as particles in the matrix of the sands and as major constituents of the shales. They are generally less than 4 microns in size and often less than 2 microns and are composed of two principal minerals:



both of which are so-called "non-swelling" clays.

The McMurray formation can also have locally, minor amounts of other minerals such as montmorillonite:



a swelling clay which exhibits extreme colloidal behavior. When this clay is present at levels of even 2 or 3 percent, such as in the Clearwater formation, it can cause serious problems for extraction and tailings disposal.

As mentioned, the clay minerals constitute less than 1% (by weight solids) in the rich oil sands, but are present in amounts of up to 50% in associated shales and lean oil sands, often imbedded in the rich oil sand as "center reject". Figure 2.2 illustrates this aspect of the oil sand. Because these "minor" amounts of clay minerals are almost solely responsible for both the extraction and the tailings disposal problems of the oil sands, they are discussed in greater detail in sections 3 and 4 of this report.

While both Syncrude and Suncor would dearly love to be able to "selectively" mine oil sand to eliminate these difficult to process and dispose materials at the mining stage, this objective has remained an elusive goal. The distinction between reject materials and lower grade oil sands can be very difficult to establish in practise, as they can look essentially the same to the naked eye and both are highly variable.

2.6 Hydrogeology

(2.6)

Over and above the depositional environment for fresh or salt water, extensive penetration of fresh surface water has diluted or washed out the connate water in many areas of relatively high permeability and hydraulic head, such that describing the connate water characteristics of mineable oil sands prior to the mining and extraction process can be a difficult task. This composition will be shown in Section 10.0 to be an important factor determining the future quality of tailings pond water and water available for recycle.

As discussed in Hackbarth, 1972, and illustrated in Figure 2.4 mineable oil sand typically has a hydraulic conductivity of 10^{-6} to 10^{-4} cm/sec, with a median of 3.2×10^{-5} cm/sec.

The presence of bitumen can significantly reduce the hydraulic conductivity of oil sand. Especially at high bitumen saturations, say above 90%, the overall conductivity may be reduced below 10^{-6} cm/sec, to values approaching 10^{-9} cm/sec. But at normal bitumen saturation values, of closer to 75%, the water conductivity of oil bearing formations is roughly comparable to surrounding soils, (i.e. about the median permeability of 3.2×10^{-5} cm/sec referred to earlier). This conductivity may well be primarily due to "reject" and aquifer zones illustrated in Figure 2.2.

The permeability or hydraulic conductivity of the oil sand in-situ provides a standard to judge the effects of the whole tailings treatments discussed in subsequent sections. Values slightly in excess of the 3.2×10^{-5} cm/sec indicated for hydraulic conductivity could be expected for the whole sand and clay minerals, if the bitumen could be removed without disturbing the relative positions of the sand and clay grains.

Obviously, achieving anything approaching such an orientation when depositing solids from a slurry would not be expected. Also from a tailings disposal design perspective unless the disposal approach is workable for materials with permeabilities within the range of Figure 2.2, it will probably not be practical at all.

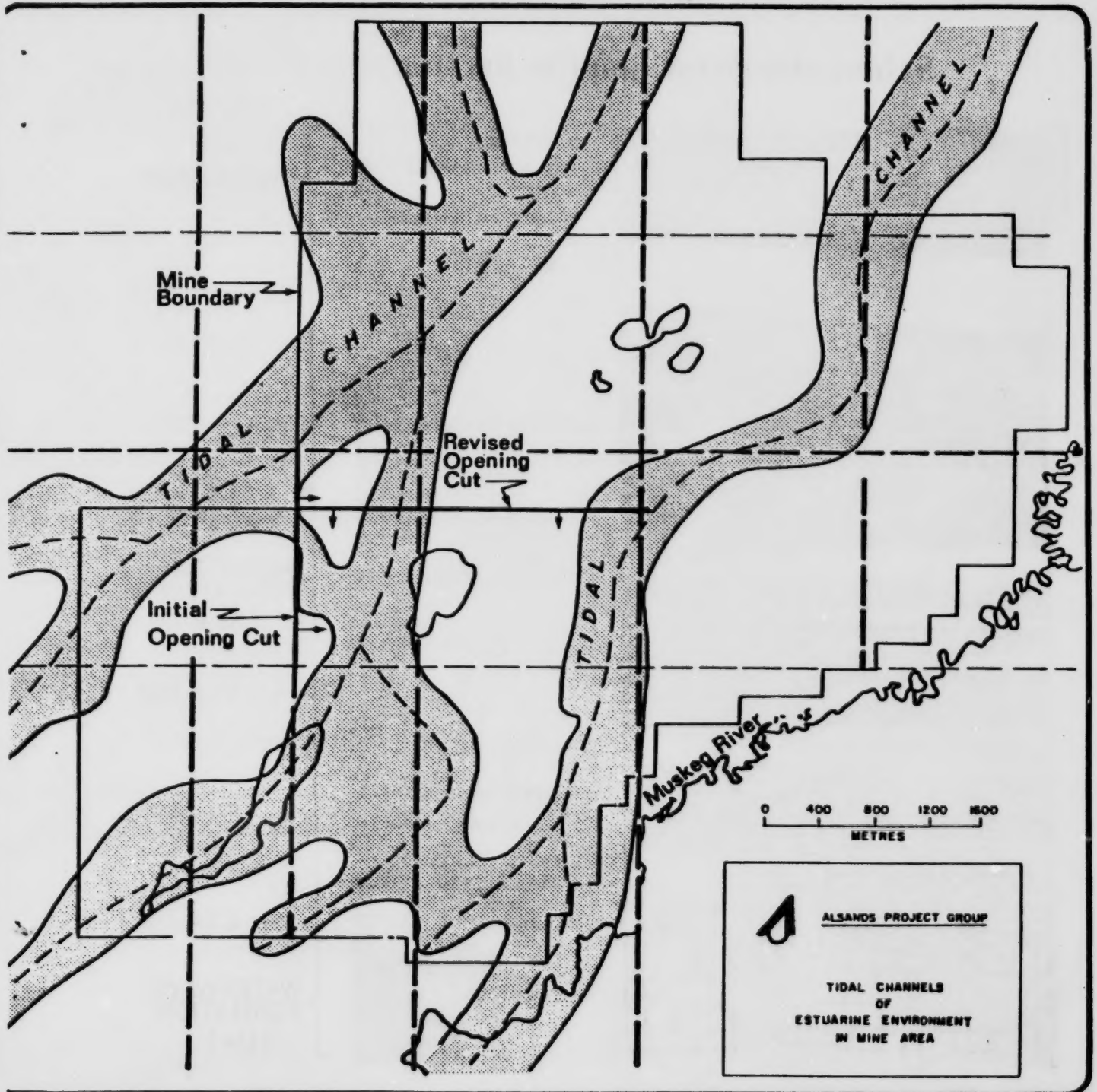
The extent to which we achieve this "perfect" alignment of clay and sand in tailings treatment could be expected to influence two principal properties of the material: the bulk density and the permeability of the material. Some considerations related to bulk density are discussed in section 4.0.

The results of tests on these properties for whole tailings are discussed in sections 7.0 to 9.0.

(2.7)

Figure 2.1

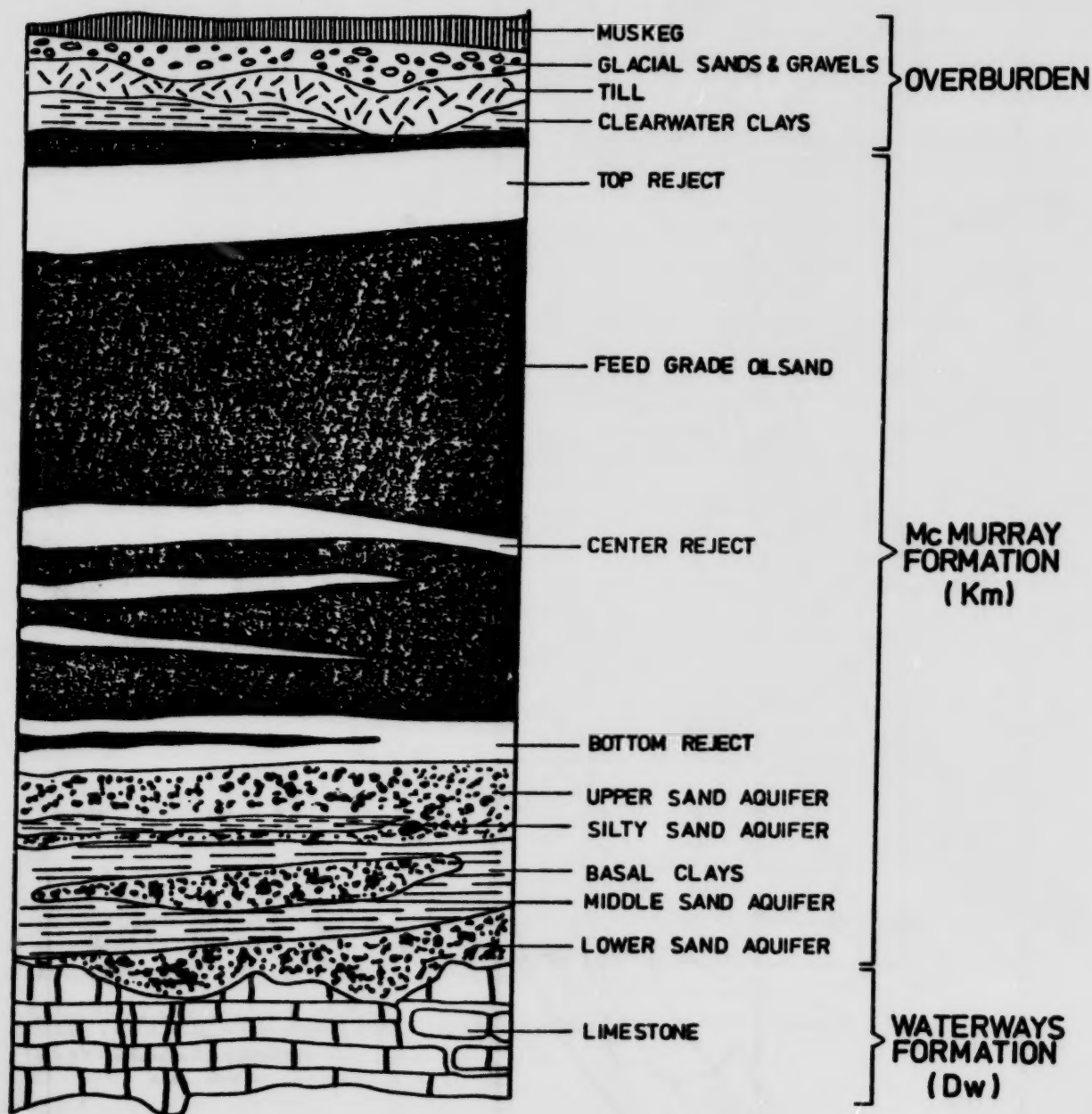
Tidal Channels Map



(2.8)

Figure 2.2

Schematic Stratigraphic Section

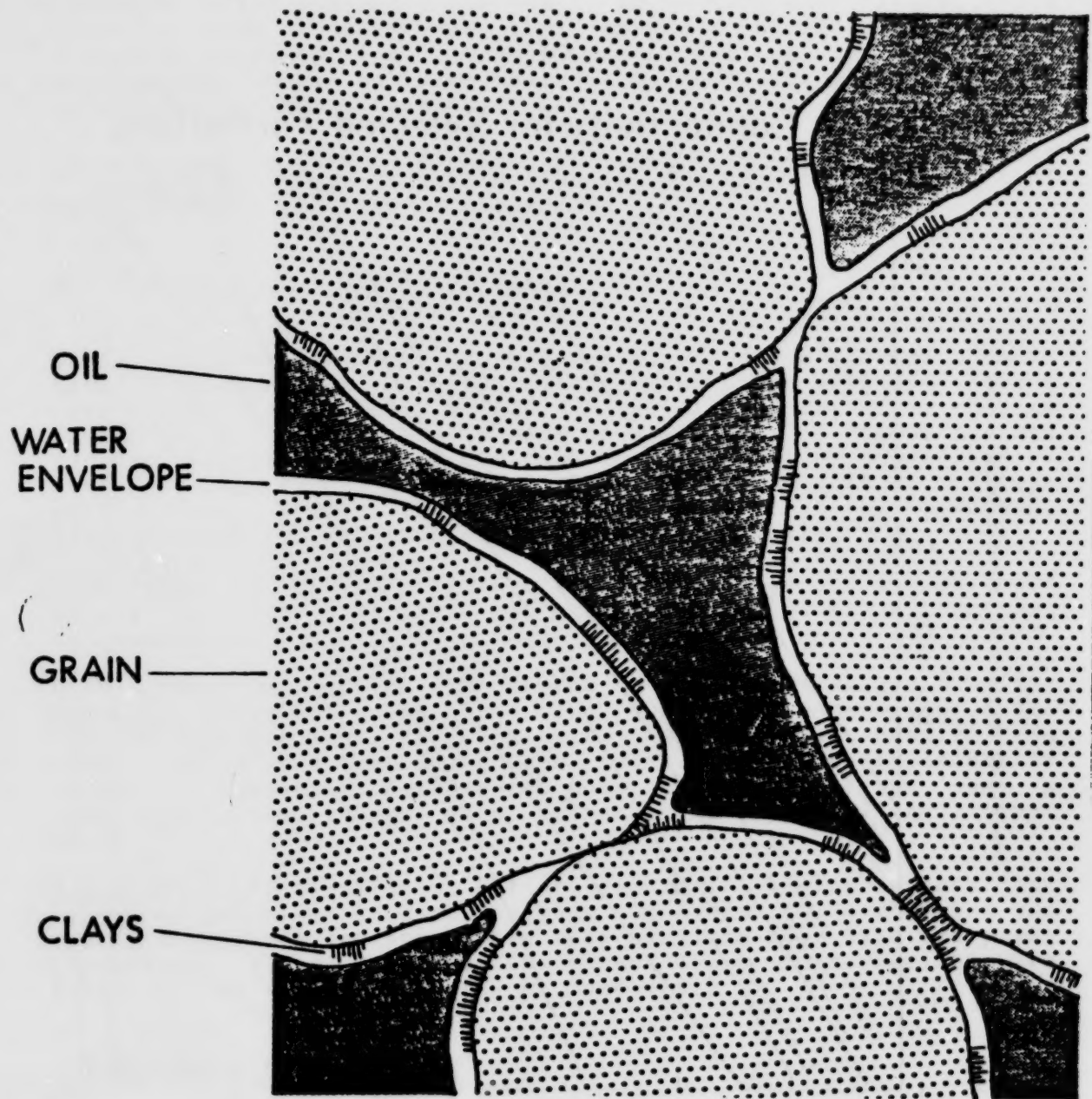


Ref: Khan, 1982

(2.9)

Figure 2.3

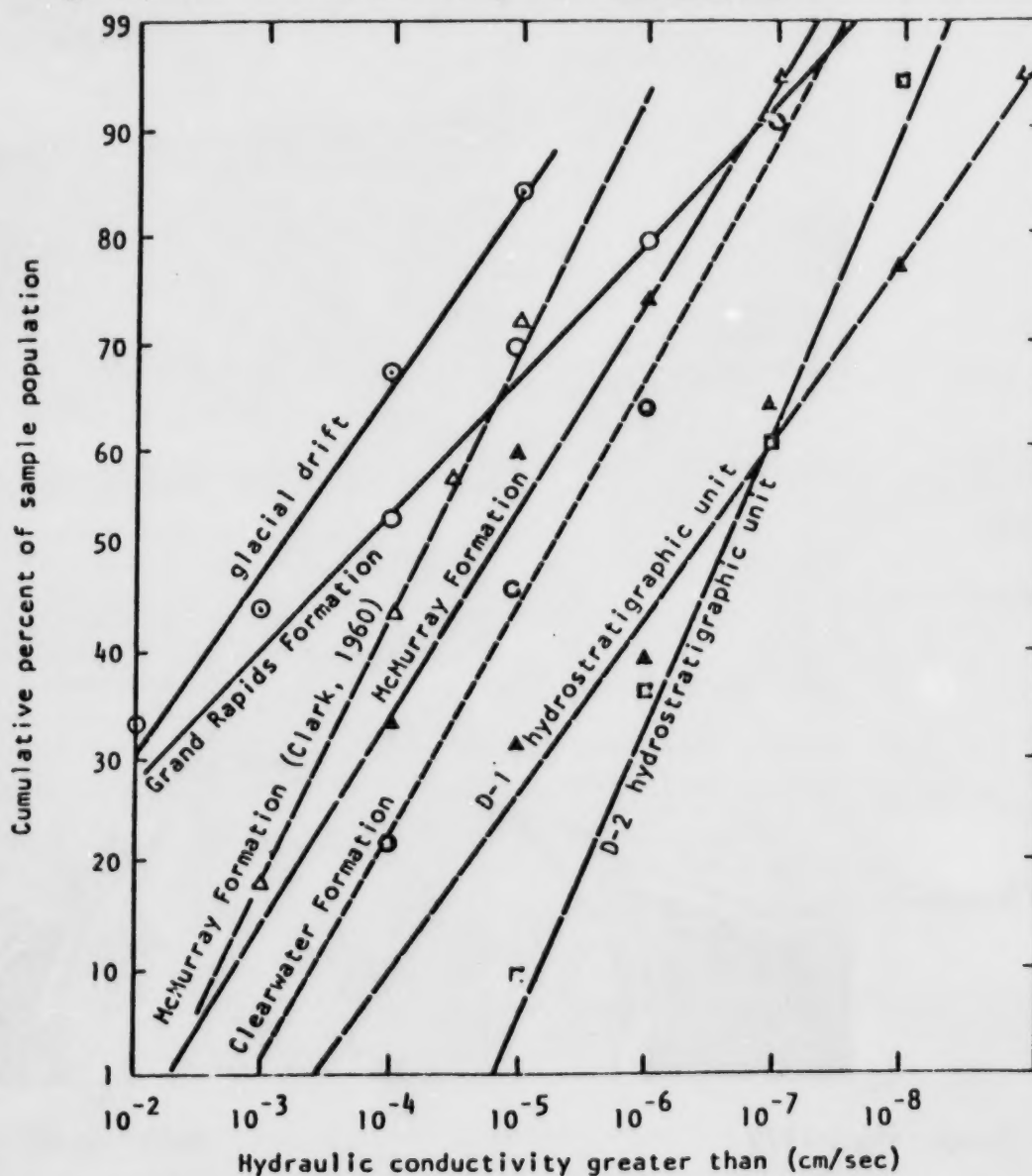
Microstructure of the Oil Sand



Ref: Humphreys, 1979

Figure 2.4

Frequency Distribution of Hydraulic Conductivity for Selected Formations



Ref: Hackbarth, 1979

3.0 OIL SAND PROCESSING

Mineable oil sand development, in addition to solving the problem of high-fines oil sand processing, required the use of "world-scale" technology for mining, upgrading, extraction and numerous other support processes to be economically viable. While there is some thought now that Syncrude exceeded the scale actually required for economic viability, at the time it was constructed, it was believed that oil sands plants should be even larger for optimum economics.

As the plants themselves are enormous, it is not surprising that their problems, such as tailings ponds, are also the largest mine waste disposal problems in the world.

3.1 The Commercial Oil Sands Plants

There are presently only two commercial oil sands plants, both in the Athabasca area of Alberta. The Syncrude plant will soon have a rated production capacity of 129,000 barrels per day of synthetic crude oil, while the Suncor plant has a capacity of 65,000 barrels per day. Approximately 300,000 tons of ore are mined and processed daily at Syncrude, generating about 250,000 tons of tailings solids. Suncor whose lease is adjacent to that of Syncrude, handles about 100,000 tons of tailings solids daily.

Production of crude oil from tar sand, as carried out at these plants, involves three principal operations: mining, extraction, and upgrading.

Both commercial operations depend on open-pit mining of the tar sand and on the hot water extraction process for separation of the bitumen from the sand. Large quantities of tailings result from this process and containing these tailings in an environmentally acceptable manner at reasonable cost has, in itself, been a challenge, even though this operation is very similar to other mines.

While there are significant differences in the mining methods and upgrading processes used at Syncrude and Suncor the extraction and tailings disposal operations are very similar. (The Syncrude plant throughput is, of course, twice as large on average, but its tailings pond is 10 x the area of Suncor's.)

3.2 The Extraction Process

The extraction process separates bitumen in the oil sand into a

(3.2)

form suitable for Upgrading. The process is shown schematically in Figure 3.1, and has the following major steps:

- * plant feed system,
- * conditioning,
- * primary separation,
- * scavenging or secondary recovery,
- * froth treatment.

3.2.1 Plant Feed System

A stockpile and reclaim system is provided in front of the extraction plant primarily as surge storage to delink the mine and extraction plant operations.

Oil sand delivered from the mine by the conveyors is either stockpiled by stackers at the entrance to the extraction plant or delivered directly to a surge bin as plant feed. The oil sand stored in the stockpile can be reclaimed by mobile equipment to supplement extraction feed during periods when feed requirements exceed mine output. The material in the bin is discharged onto apron feeders, weighed and fed by inclined conveyors into parallel processing lines for extraction.

Oil sand fed to the extraction plants averages about 12 weight percent bitumen, for Suncor and slightly under 11 wt. % for Syncrude, with a range of from about 6 - 14%. The average fines content also varies by several percent between the two plants, with Suncor averaging about 10% and Syncrude about 13% with a range of something like 3 to +20% fines. Both plants have shown gradual trends in ore quality as mining progresses through different portions of the ore bodies. Readers who are interested in plant feed and performance characteristics may find it informative to review the publication "Oil Sands Plant Statistics" by the E.R.C.B.

3.2.2 Slurry Conditioning

Disintegration or digestion of the oil sand into bitumen which will float and waste sand and clay uses a "conditioning drum" which is similar to an autogeneous grinding mill. The drum however, rotates at a much lower velocity than typical grinding mills and also injects steam beneath the slurry surface to raise the temperature to about 85°C. Caustic and water to form about a 25% water slurry are added to the oil sand ore at this stage to produce a thick "self ablating" pulp which is conditioned for about 4 minutes.

An important secondary function of this process may also be the

(3.3)

introduction of a relatively small but critical amount of air required to "float" the bitumen in the subsequent primary separation processing operation.

3.2.3 Primary Separation

Separation of the dispersed bitumen from the conditioned pulp is accomplished in a primary separation vessel (P.S.V.) by diluting the pulp with hot water and recycled middlings (the central layer in the separation cell), then holding it in a quiescent state. The use of middlings recycle reduces the hot water make-up requirement, which is governed by the amount of fines in the oil sand feed. The water rate is adjusted to control the middlings density/viscosity. The coarse sand particles rapidly settle to the conical bottom of the primary separation cell while the bitumen rises, forming a frothy layer on top of the cell. This layer, referred to as primary froth, is skimmed off and pumped to the froth treatment plant. The sand in the cell bottom is continuously raked to a central discharge cone from where it is pumped after dilution to the tailings pond.

The extraction process is believed to be adversely affected by a number of contaminants in the process water including multivalent cations such as Fe^{+++} , Al^{+++} and Ca^{++} . NaCl is also believed to be harmful to the process if it builds up to a sufficiently high level in the process water.

Published data is lacking on this subject but it is suggested that concentrations of multivalent cations in excess of perhaps 30 mg/l would be cause for concern, as might chloride levels of 1500 ppm or more (S.J.L., personal opinion).

The well known problem of processing high fines oil sand also can become severe at $\bar{X}$ -44 μm (the traditional measure of fines) levels of perhaps 14-16 wt %. The typical operator control response when high fines oil sand is encountered is to increase both the caustic level and the water addition rate, (e.g. E.R.C.B., 1984). Even with caustic levels quadrupled and water consumption doubled, severe processing problems with fines may continue or worsen.

The fines, consisting essentially of silt and clays from the oil sand, sometimes do not have a high enough settling velocity and tend to accumulate in the middlings. Small bitumen globules with relatively little air attachment, also tend to have low rise velocities and accumulate in the same mid portion of the P.S.V. This accumulation increases the viscosity in the cell and retards the rate of rise of the bitumen globules and rate of settling of fines even further. The fines must be continually withdrawn from the central layer in the cell in the form of a dilute middlings

(3.4)

slurry; an accumulation of fines or bitumen may cause the viscosity to build up rapidly until separation of the bitumen ceases. This is the so called "setting-up" of the P.S.V. The middlings withdrawn contain significant quantities of bitumen for which further recovery is attempted in the subsequent scavenging circuit.

3.2.4 Scavenging

In the scavenging operation, essentially conventional mineral flotation cells are employed. Air is injected into the middlings which are mechanically agitated to promote the formation of a bituminous froth. The recovered froth is sent to a settler to improve its quality, after which it is combined with froth from primary separation and sent to froth treatment.

High water content tailings from the scavenging operation are used as flush water for the primary separation tailings for disposal to the tailings pond.

3.2.5 Froth Treatment

In the froth treatment plant, the combined froth from the primary separation and scavenging operations is treated to provide a suitable feedstock for the upgrading plant. The froth is first heated then deaerated prior to dehydration and demineralization by dilution centrifuging.

Dilution centrifuging utilizes naphtha, an upgrading recycle material, as a diluent to reduce the specific gravity and viscosity of the bitumen, with the result that the entrained solids and water, which are denser than diluted bitumen, can be segregated by mechanical means such as centrifugation. Syncrude uses "heart-cut" hydrotreated naphtha for this operation whereas Suncor uses "raw" coker naphtha.

The diluted bitumen is centrifuged in the primary solid-liquid separators or scroll centrifuges at relatively low gravitational forces to remove the larger mineral particles. Cuno filters are used to remove fossil wood and straw fragments from the froth, so called "birds nests" prior to high speed centrifugation. The high gravity high speed secondary solid-liquid-liquid separators or nozzle centrifuges further reduce the mineral and water content. Diluted bitumen is then stored in surge tanks prior to feeding it to the upgrading facility.

The Froth Treatment Plant tailings can be pumped separately to a localized area of the tailings ponds to permit skimming of

floating diluted bitumen and perhaps in future, heavy minerals recovery. Neither Syncrude nor Suncor currently attempt to segregate or recover oil or minerals from this stream, though tailings oil recovery is planned for the near future at Syncrude. Figure 3.2 provides a process material balance as (somewhat optimistically in S.J.L.'s opinion) forecast by Alsands.

3.3 Bitumen Recovery

The selection of the Hot Water Process is predicated on its commercially proven technical and economic viability and its reliability in recovering bitumen. The recovery efficiency is directly related to the bitumen content and inversely related to the fines content of the plant feed as the correlation in Figure 3.3 suggests. The extraction plant recovery at Syncrude and Suncor is typically in the range of 80 - 92%. For some information on this subject, see E.R.C.B., 1983 monthly statistical supplements. Froth treatment at Suncor recovers about 98% of the hydrocarbon content of the froth; Syncrude's hydrocarbon recovery may well be even higher using slightly improved equipment. However, naphtha losses in the tailings from the centrifuge plant further reduce the hydrocarbon recovery. Syncrude is currently implementing a steam stripping process to recover naphtha lost in d.c. tailings.

3.4 Water Management

Water management is a critical concern in the operation of an oil sand plant. It requires the maximum utilization of recycle water. It also requires treatment and consumption of large amounts of fresh water.

3.4.1 Fresh Water Requirements

The average fresh water requirements for a typical hot water based oil sand plant are about 1.02 tonnes of water per tonne of oil sand in the first few years and less in subsequent years. (It is necessary to accumulate an inventory of water in the tailings pond as initial settling occurs, which usually takes about three years.) Typical water balances for these two periods are illustrated in Figures 3.4 and 3.5.

During normal operation, after water recycle is established from the tailings pond, the average fresh water requirement may be reduced to about 0.34 t/t of oil sand feed for the remainder of the life of the plant.

(3.6)

The E.R.C.B. Bitumen Extraction Process Evaluation provides data on the impact of oil sand grade on water consumption; it nearly doubles when the bitumen grade drops from 12 to 8 percent (E.R.C.B., 1984).

The frequency of incidents of "setting up" the PSV's also increases dramatically at the lower grade of oil sands, necessitating more frequent "dumps" of PSV) contents to the tailings pond.

3.4.2 Fresh Water Source

The fresh water requirements for both plants are met by pumping water from the Athabasca River, through holding/settling ponds. The use of river water is deliberately minimized by using local surface runoff and subsurface water and by maximizing tailings pond recycle water.

3.4.3 Tailings Disposal

The Extraction Process produces two separate tailings streams, extraction tailings and froth treatment tailings. These streams are currently co-mingled in the extraction plant for pumping to the tailings pond.

The extraction tailings containing sand, silt clay and residual bitumen are a dense slurry with 45 to 55 weight percent solids. This stream represents about 97 percent of the mineral from the Extraction Process. Several extraction tailings lines are used to transport the total amount of tailings produced, 4 in Syncrude 's case and 2 in Suncor's.

Froth Treatment tailings contain silt, clay, water, and a much higher concentration of residual bitumen and naphtha than extraction tailings, as well as a concentrated heavy minerals fraction.

3.4.4 Water Recycle

Clarified water from the tailings pond with less than 1.0 percent solids, as dictated by process considerations, is decanted by barge mounted pumps and stored in a recycle water basin. This water is mixed with recycle process water and river water as required and recycled for use in the upgrading process and extraction plant, and as sluicing water in the tailings system.

Tailings pond water recycle can commence within 2 or 3 years after plant start-up when adequate volumes of clarified water are

(3.7)

available. Process water is recycled immediately after start-up.

After evaporation losses, entrainment in the sand dykes and retention of water in the sludge, about 65 percent of the water in the tailings may be available for recycle.

The tailings pond water balance is discussed in more detail in section 4.0.

3.4.5 Extraction Plant Emergency Dump Ponds

The plants require emergency dump ponds, in the event of equipment failures with facilities to pump the contents to either conditioning, separation or tailings on a controlled basis to attempt to reclaim bituminous material or dispose of water and solids as required.

3.5 Process Economics

The hot water and tailings disposal processes constitute only a minor portion (less than 15%) of the capital investment and a similar portion of operating costs in a mineable oil sands operation, with the mining, upgrading and utilities plants being considerably more capital and operating cost intensive.

In a sense, due to its relatively low capital and operating costs, the ability to separate bitumen from sand and clay via the hot water process is the most crucial factor in economic processing of mineable oil sands. While research continues on other extraction and processing alternatives, the methods which have been developed to-date have questionable economics relative to hot water processing.

It is not suprising the industry has not implemented solvent based or dry processing technology which might increase cost with no increase in recovery or reliability - although the offending tailings ponds might be eliminated.

Figure 3.1

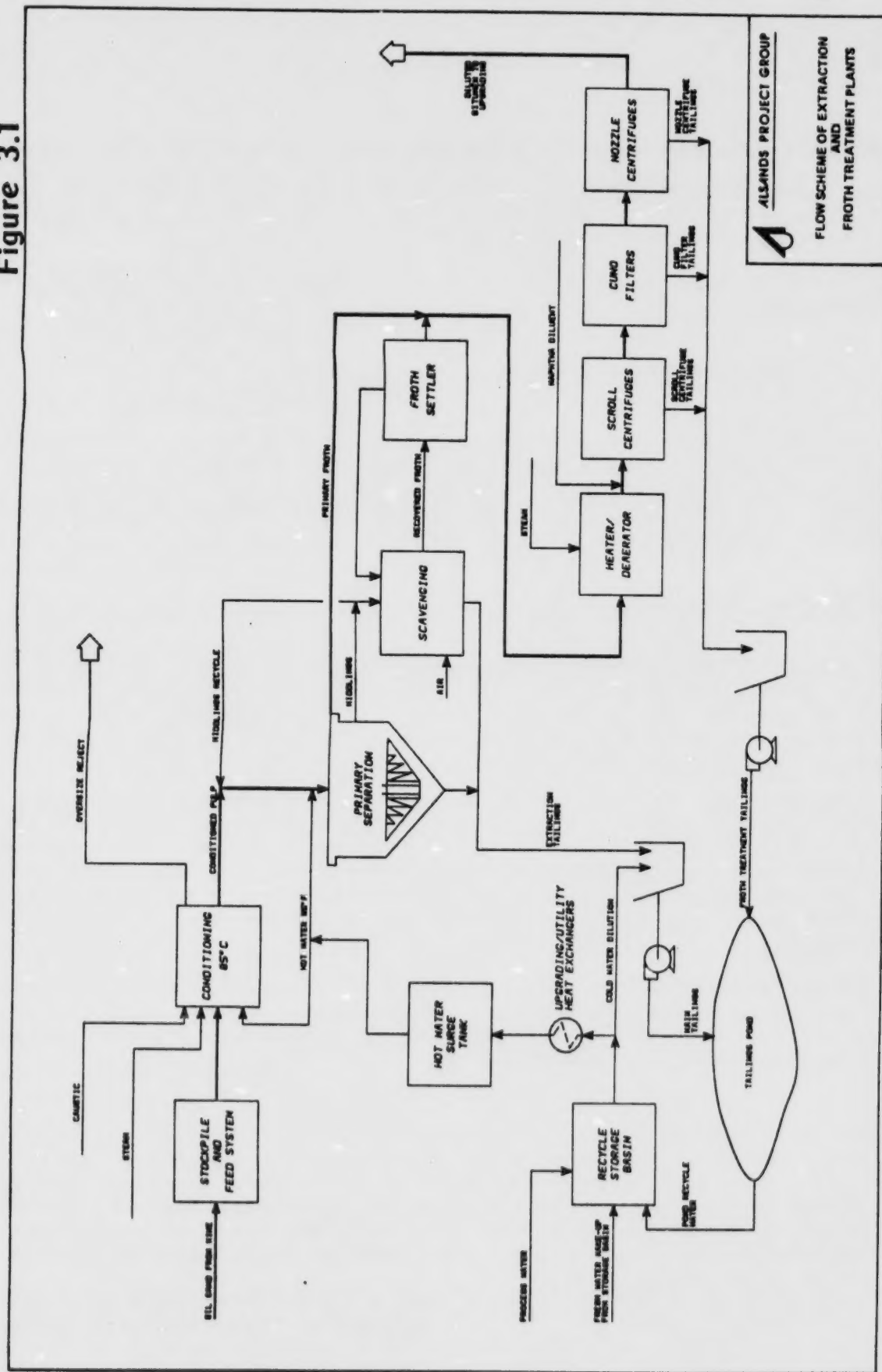
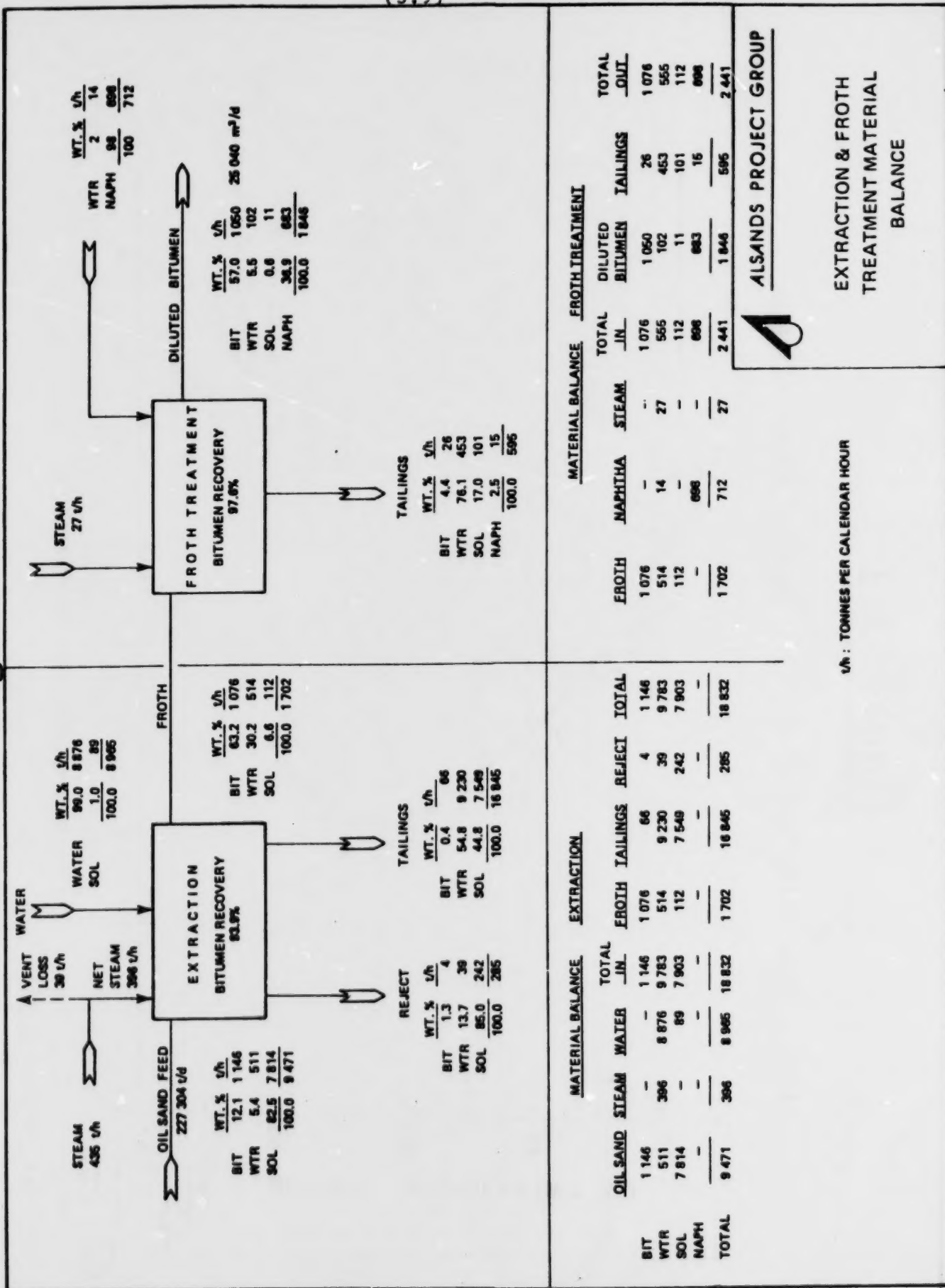


Figure 3.2



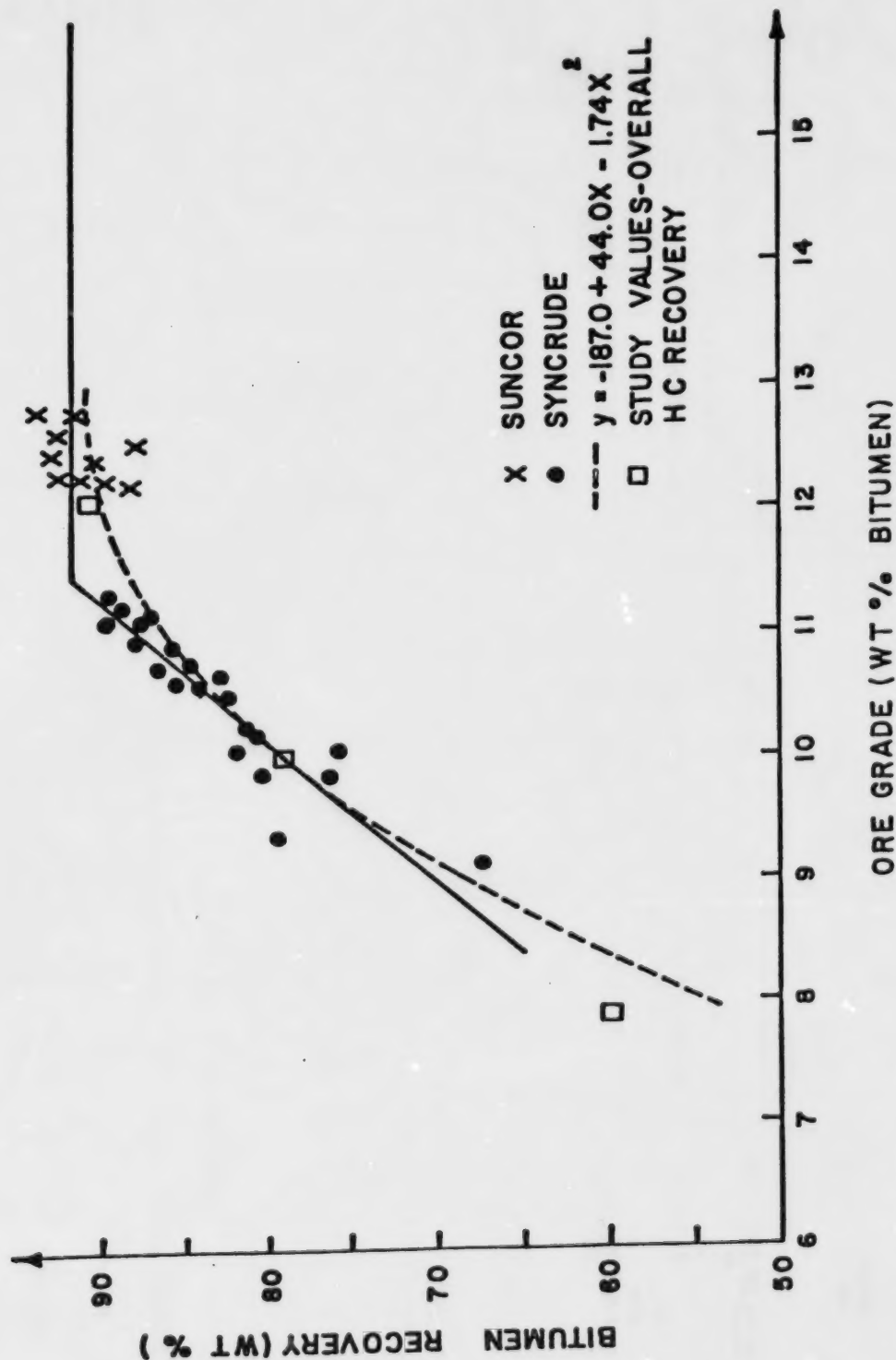
ALSANDS PROJECT GROUP

EXTRACTION & FROTH
TREATMENT MATERIAL
BALANCE

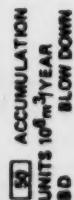
u/h : TONNES PER CALENDAR HOUR

Figure 3.3

Extraction Efficiency vs. Oil Sands Feed Grade

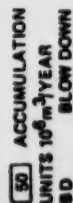


(3.11)



**OVERALL WATER
BALANCE
YEARS 1 TO 3**

(3.12)



**OVERALL WATER
BALANCE
YEARS 4 TO 25**

4.0 TAILINGS DISPOSAL AND WATER RECYCLE

An oil sands tailings pond is not just a waste "dump". The pond(s) functions as a solids removal system for water recycle; oil sands plants gulp water at a prodigious rate and try and reuse as much of it as possible. (Syncrude has achieved as much as 100% water recycle for extraction, for short periods of time, with typical recycle levels of 50 to 65% of total extraction water use.

There is a maximum level of suspended solids in the reclaim water which can be tolerated in heat exchange (perhaps 3%) and in the extraction process. Syncrude's reclaim water is typically less than 1.0% solids and has even been below .1% solids for extended periods of time.

In addition to solids removal, the recycle of alkaline water allows some reduction in extraction plant caustic consumption and has even lead to the ability to slightly reduce heat loads at Suncor, during the Summer months, as their tailings pond stays slightly above ambient temperatures.

Both Syncrude and Suncor also have various schemes for recovery of additional oil from the tailings ponds. The accumulation of oily sludge in the ponds is sometimes suggested as beneficial to the ultimate maximum recovery of bitumen from the resource, as it does allow for additional reprocessing more readily than for "dry" solid wastes.

While very little has been published, there have been concerns that recycle of extraction process water could lead to high salinity levels. As indicated in section 3.0, salinity derived from connate and mine depressurization water, in excess, is believed to adversely affect the extraction process, reducing bitumen recovery and froth quality in the extraction process. Preventing excess recycle water salinity is the rationale for Syncrude's disposal of saline mine depressurization water to Poplar Creek, rather than to the tailings pond, as proposed by Alsands (Alsands, 1978), although the amount of water going to Poplar Creek is expected to be lower in future.

While there are no clear indications that Syncrude will encounter water quality/extraction efficiency concerns within the expected 25-year life of the plant, a number of factors could result in this becoming a significant problem for them. Careful pond water quality monitoring and a predictive capability for water quality are important to avoiding a potential problem in this area. Suncor's connate and mine depressurization water are much closer to fresh water, (probably due to high hydraulic heads near the Athabasca River) and water quality concerns of this nature are not expected to arise in their operations. Their concerns with water quality relate mainly to solids, caustic and bicarbonate levels

(4.2)

and their impact on extraction efficiency.

Tailings leaving the Extraction Plant at 45 - 55% solids will immediately form two distinct phases: a coarse sand deposit and a dilute silt/clay sludge if slurry velocities drop below about a metre per second. The coarse fraction can be used for dyke building (as discussed later) and the sludge fraction is impounded in the pond. As the sludge settles, water is released and can be returned to the Plant as process water. However, after a few months of settling, the sludge reaches a state of pseudo-equilibrium and further consolidation takes place at an extremely slow rate.

The equilibrium condition occurs at solids concentrations between 20 and 30 percent by weight (about 10 to 15 percent by volume). Although the sludge phase contains a relatively small percentage of the total tailings solids, the volumetric contribution of the sludge phase is very significant due to the large volumes of water associated with it.

The sludge accumulation rate is naturally dependent on the fines level of the Extraction Plant tailings. Figure 4.1 shows a size distribution curve typical of Syncrude tailings. On average, 12% of the feed solids will be of -325 mesh size (-44 micron), as illustrated by curve 1.

Generally, oil sand tailings are deposited in oil sand disposal ponds in such a manner that three separate solid phases are generated. Each has distinctive properties. These properties are summarized as follows:

°Dyke Sand: captured by the cell construction technique; the material is utilized to construct the retention pond dykes

Fines content

Representative Grain Size Distribution

3 to 4%
See Figure 4.1,
Curve 2
1570kg/m³
30°

Typical Density (dry)

Effective Shear Strength ()

°Beach Sand: deposited during the overboarding procedure as the tailings are rapidly discharged into the pond.

Generally contain a mixture of sand and fines in varying proportions but generally with the fines content increasing downslope.

Fines content

Representative Grain Size Distribution

3 to 15%
See Figure 4.1,
Curve 3
1600kg/m³
25° to 30°

Typical Density (dry)

Effective Shear Strength

(4.3)

^oSludge: generally a solid-water suspension found in the central area of the discharge ponds. The suspension contains 10 - 20% solids by volume, (including silt and clay).

Fines content	90 - 100%
Representative Grain Size Distribution	See Figure 4.1, Curve 4
Typical Density (bulk)	960kg/m ³ to 1300kg/m ³
Effective Shear Strength	Nil (thixotropic fluid)

4.1 Bulking Factor

Figure 4.2 illustrates graphically the dramatic influence that sludge production can have on the volume of tailings that must be accommodated. Camp, 1976 indicated that GCOS, during their first five years of operation, experienced an overall bulking factor of about 1.4. That is, the waste products from the extraction process occupied 40% more volume than did the ore which was mined. Syncrude, GCOS, governmental research organizations, and numerous others have spent a great deal of time, effort and money searching for ways and means to reduce the rate of sludge accumulation and the bulking factor from the hot water extraction process. Although some successful techniques have been identified, none to date have been proven economically feasible on a commercial scale.

As a primary consequence of the high bulking factor, storage capacity must be provided for a considerable volume of tailings outside the area of the mined-out pit. The nature of the mining is also such that primarily due to drainage problems, it is impractical to deposit tailings in the mine pits for about the first six to ten years of mine operation.

Also, when the in-pit volume requirements of overburden and centre reject disposed of in the mine pit are considered, only about 5 years of Syncrude's tailings production (20%) can actually be returned to the mine pit.

4.2 Grain Sizes and Mineralogy

Wastes generated by the extraction process are composed largely of fine quartz sand. A typical range of grain size analysis of total tailings as experienced at Suncor (Camp, 1976) is as follows:

(4.4)

<u>Sieve Size</u>	<u>Percent Finer</u>
	Range
100	85 - 95
150	47 - 75
200	18 - 45
325	6 - 34
0.02 mm	0 - 6

A typical mineralogical composition of total tailings obtained from (Camp, 1976) is 85 percent quartz, 9 percent clay minerals, and 6 percent feldspars with trace amounts of heavy minerals. There is some disagreement among knowledgeable observers as to whether Suncor's problems initially were worse due to high clay materials from the clearwater formation. In any case, their recent experience with the volume of tailings being produced, seems to be, if anything, lower than in their early operations.

The slimes fraction of the tailings or material found in the sludge fraction is sized as follows:

<u>Sieve Size</u>	<u>Percent Finer</u>
50	100
100	99
200	96
325	94
0.02 mm	89
0.01 mm	82
0.004 mm	33
0.001 mm	12

A typical range of mineral compositions for the minus 2 micron fraction as actually experienced at Suncor is as follows (Camp, 1976):

<u>Mineral</u>	<u>Weight %</u> (1966 Pilot)	<u>Weight %</u> (1974 Commercial)
Kaolinite	22	76
Quartz	19	7
Mixed Layer	11	3
Illite	10	7
Feldspar	10	trace
Montmorillonite	9	1
Calcite	7	1
Dolomite	7	trace
Chlorite	5	3
Siderite		1
Ankerite		1

Although the minerals in oil sands are highly variable, the important properties of both the clay fines and the tailings which make the sludge problem what it is can be reasonably well

understood in terms of two primary clay components, kaolinite and illite. Although the data is highly variable as to the clay mineral composition, the tailing sludge clays can be thought of as averaging about 2/3 kaolinite and about 1/3 illite and most of the other minerals such as montmorillonite can be ignored for many purposes. (Some observers believe that montmorillonite is only present in significant quantities +3% in the Clearwater formation, not normally mined as oil sand feed. It is occasionally included in feed grade material accidentally.) The properties of clay minerals, particularly kaolinite and illite are discussed in some detail in Section 5.0.

The tailings as produced have typically been treated with about 0.02 to 0.05 percent NaOH and are at a pH of 8.0 to 9.0, the extraction plant conditions used to deliberately disperse the clays. The dosage of NaOH as discussed earlier, is highly dependent on feed grade, with lower grade oil sand requiring higher caustic levels.

Projected settling rates for the Syncrude slimes suggest periods of up to 3 years as shown in Fig. 4.3, will be required for sedimentation to 0.35 tonnes per cubic metre which will be near the maximum that can be obtained in the settling pond.

The clay constituents in the minerals of the oil sands are characterized by a number of properties such as small size, high charge and platelet shape which make their separation from the water phase a slow and difficult process. Many of these properties also have particular significance to the lime treatment process, but the use of huge tailings ponds such as at Syncrude is predominantly the result of these colloidal clays having settling rates which require decantation for years. Ultimate compactions only reach 30-35% solids even with years of settling. (The presence of quartz sand and silt grains co-deposited with the clay grains in tailings sludge is known to significantly improve this density.) A 35% solids sludge slurry is a thixotropic liquid, much like ketchup in behaviour. It would flow out of the dykes readily if they were breached.

4.3 Dyke Construction

Syncrude's tailings production rate of 225,000 tonnes of solids per day at a bulking factor of 1.40 requires handling and storage of some 170,000 cubic metres of sand tailings and 50,000 cubic metres of liquid sludge per day. (The current tailings bulking factor, in practise, at Syncrude, may be closer to 1.3 than 1.4 with 1.35 perhaps representing a better average. 1.4 has been commonly adopted as a "typical" bulking factor.)

4.3.1 Mildred Lake Tailings Pond

The Mildred Lake Tailings pond, as shown in Figure 4.4 covers an area of about 24 km² (9.4 miles²). The dykes will ultimately range in height from about 25 metres on the west side of the pond to a maximum of about 90 metres at the north end of the Beaver Creek Valley. At an estimated final crest elevation of 345 metres above sea level most of the dyke will be about 50 metres higher than the surrounding terrain.

Starter dykes were used at either end of Beaver Creek Valley and at the Mildred Lake crossing where the edge of the dyke touches Mildred Lake (Mildred Lake is a natural lake which is used as a raw river water storage pond.) These were constructed of borrow materials, by earth moving equipment. The north and south starter dykes provided storage space in Beaver Creek Valley for the initial tailings disposal after plant start-up, while the Mildred Lake crossing avoided potential problems there with hydraulic construction. As tailings sand became available, all subsequent dyke construction has been carried out hydraulically. Sufficient dyke height is constructed during the summer months to allow for the level the pond will reach the following Spring, plus a safety factor. Some of the equipment and crews used for hydraulic dyke construction in Summer are employed for muskeg removal in winter to improve equipment utilization and give personnel year round work.

Because the dyke foundation conditions vary over a wide range of soil types, the width and angle of the side slopes is varied. There are three principal soil types which required changes in construction:

- (i) muskeg overlying soft organic and inorganic silts and clays;
- (ii) highly plastic weathered and "slickensided" bentonitic clay shales;
- (iii) alluvial, highly permeable sands and gravel.

Sand tailings dykes for oil sand tailings are constructed with a maximum downstream or outside slope of 2.5 to 1 (horizontal to vertical), with (as indicated in Figure 4.5) slopes as low as 9 to 1 for the poorest foundation soils (for Syncrude's cell 18).

Syncrude has especially serious foundation soil properties on the northwest end of the starter dyke, cell 18 as illustrated in Figure 4.5. In this case, the dyke slopes were first increased to 6:1 and then later to 9:1. Lift heights were also reduced from 3 metres to 2 metres. This would result in less over pressure and more time for pore pressures to dissipate than the 3 metre dyke heights originally planned. This has proven an effective method of controlling the problems of unstable foundation soils; the original problems of settlement and pore pressure observed in this

area have been eliminated since 1982 (Handford, 1982); Syncrude will also make extensive use of the so called "observational approach" in the design and modification of the seepage control system for the tailings dykes. This should be effective in maintaining the "phreatic head" within the tailings dykes at acceptable levels.

Figure 4.6 illustrates a typical alignment of tailings lines and associated oil recovery skimmers, during the period when over-boarding is occurring. During the construction season of May to October the coarse sand tailings are hydraulically placed in the structural portions of the containment dykes. Clarified water, as the fines settle out, is recycled from the pond to the extraction plant. Excess sand, not required for dyke construction, is overboarded into the pond to form relatively flat lying beaches against the compacted sections of the dykes.

The sand dykes are constructed by the "hydraulic cell" procedure with the "upstream" method, described in section 4.3.2. Seepage control through the dyke is provided by internal strip drains as illustrated in Figure 4.7.

Although the design and construction concepts for the Syncrude dykes are essentially the same as those used for the Suncor dyke, Syncrude's foundation and operating conditions are more difficult. The more critical design aspects at Syncrude warrant more elaborate continuous monitoring during ongoing annual construction to permit design optimization as information on the rate of underlying soil compaction and seepage rates becomes available.

The main features of the design concepts (which are significant to both conventional disposal and the disposal of whole tailings) are discussed in what follows.

4.3.2 Sand Dykes

The design cross-section for sand tailings dykes is illustrated in Figure 4.7. The sand embankments are designed as hydraulic fill structures with compacted downstream shells having an irregular upstream boundary against uncompacted tailings.

For this design approach, the thickness of the compacted shell in any horizontal plane must be sufficiently large to resist the hydrostatic pressure from the pond and the total pressure from the uncompacted sand above it. This approach has been developed by trial and error over centuries for the design of hydraulic fill dams and typically involves a significant margin of safety.

Extension of the compacted zone over the uncompacted tailings, by so-called step over construction can lead to liquefaction

failures. It must be carefully monitored.

The sand in the dykes is placed by the hydraulic cell method, illustrated in Figure 4.9. Total tailings are discharged into rectangular cells within the structural portions of the dykes. The sand tailings as they are placed are compacted by dozer motion track packing. Excess water, containing silt and clay fines in suspension, is discharged into the pond through an overflow weir. Excess sand, not required for dyke construction, is overboarded into the pond and becomes an integral part of the tailings dyke as a relatively flat lying beach against the compacted section.

The upstream method, as used for oil sands dykes is preferred in tailings dam construction, where possible, as it is the lowest cost method of dyke construction. This type of construction is, however, not usually feasible for large dams for fear of inclusion of layers of soft slimes (fines) within the dyke section. The success of the upstream construction method for tar sand tailings dykes, to a large degree, is the result of the relatively coarse particle grain size distribution of the tar sand tailings, which are coarser than tailings from most mining processes. They contain only about 17 percent material finer than 200 mesh size or 12 percent finer than 325 mesh size, as shown in Figure 4.1.

4.3.3 Seepage Control

Seepage control is a crucial factor in the design of tailings dams. Seepage control:

- (i) maintains the phreatic surface within the sand embankment for geotechnical stability.
- (ii) controls pollution of groundwater systems outside the pond.

Seepage control is most easily accomplished by internal strip drains placed within the sand embankment. Good quality filter gravel is, however, required for these strip drains to avert the danger of "piping" and to safely collect and convey the seepage water to where it can be pumped back into the pond.

At the Suncor site, a by-product of their upgrading process, delayed-coke has the ideal structural characteristics for use in the strip drains, as in Figure 4.7. Gravel is in relatively short supply in the Fort McMurray area and when available it must be washed and crushed to meet rigid gradation specifications required for the filter materials, at considerable cost.

The potential use of "geotextiles" to minimize the size of filter drains has been investigated by Syncrude, but was apparently rejected by Alberta Environment, based on the lack of long term durability data for the filter materials.

The recommended filter design currently utilizes three strip drains at approximately 15 metre vertical spacing as shown in Figure 4.7.

All along the east and southeast portions of the Syncrude pond, relatively permeable sand deposits have been identified in the foundation soils. Periodic checks of groundwater quality from monitoring wells is used to determine whether seepage into the water table is occurring.

4.3.4 Control of Liquefaction

Tar sand tailings sand is highly susceptible to liquefaction in a low density, saturated state. The design and construction procedures are, however, such that loose sand deposits are not included in the critical portions of the embankment during hydraulic placement.

The downstream portion of the embankment, as shown in Figure 4.6, is compacted to a minimum relative density of 70 percent to eliminate the risk of liquefaction failure in the downstream direction. Experience with tar sand tailings materials, however, indicates that the overboarded sand forming the beach upstream of the compacted sections settles to an initial relative density of about 40 percent if deposited above water and less than 30 percent below water. The overboarded sand upstream of the compacted shell undergoes considerable further densification under the weight of the subsequent sand placed above it. At depths of 35 metres or more, the densities in the "uncompacted" sand may be comparable to those in the compacted shell.

The upper portions of the compacted section of the dykes are extended over the overboarded beach sand by stepover construction as shown in Figure 4.7. Occurrences of localized instabilities in the uncompacted beach and dyke following periods of accelerated sand placement have been reported at both Suncor and Syncrude. Constant monitoring during rapid sand buildup is required. Rates of sand buildup during overboarding and/or stepover construction are controlled to allow time for drainage and dissipation of excess pore pressures to avoid possible liquefaction failures.

At the more critical locations such as the Syncrude North and South Starter Dykes indicated in Figure 4.4, the beach material to be stepped over is instrumented at various depths with fast reacting piezometers for continuous monitoring of pore pressures to ensure that excess pore pressures do not develop while stepover construction is in progress. If excess pore pressures begin to develop at a given location, construction is temporarily moved to another location until pore pressures dissipate to an acceptable

level.

4.3.5 Instrumentation and Monitoring

Measurement of dyke performance through instrumentation is an essential part of dyke monitoring.

Pore pressure is monitored by installing piezometers during construction. Settlement gauges and tiltmeters can be added at critical locations of concern.

Seepage through the dykes at Syncrude is contained by interceptor ditches and pumped back into the pond. Seepage is at its maximum intensity, however, during construction, when in addition to seepage from the pond, large volumes of construction water being used for hydraulic placement of sand percolate downwards. Due to the hydraulic placement, a large variation in permeability values for the sand occurs in both horizontal and vertical directions and with depth, making seepage analysis difficult. Average horizontal permeability is considered to be about 4x vertical permeability.

4.4 Reclamation and Revegetation of Pond and Dykes

A chief concern with tailings disposal has been that the fines portion even in its settled state, achieves an ultimate compaction of only 35% and is still in a fluid state. The reasons for this will become more obvious on discussion of the properties of these fines in Section 5.0. No current technology is capable of economically reclaiming and revegetating this clay sludge material, although a number of options show technical promise. In Syncrude's case this will mean that, at the conclusion of the project, an area of 24 km² (9.4 square miles) will be buried under a fluid sludge lake. In addition to the liquefiable "solids," the Syncrude and Suncor ponds have a highly toxic water phase which has been shown to kill 50% of exposed rainbow trout in 96 hours at only a 4% concentration (MacKinnon, 1981).

With current technology, these tailings ponds will require permanent maintenance to prevent a catastrophic failure of the dykes and inundation of areas downstream of the oil sands plants for a very long time after the conclusion of the current commercial projects. While Syncrude is committed to "reclaim" its tailings pond at the conclusion of the project, this may mean only that the pond would be somehow rendered non-toxic to the environment and that methods of revegetating the surrounding dykes to eliminate the maintenance difficulties be demonstrated.

It has been shown that extensive modification of the sand material

(4.11)

used in tailings dykes by peat and fertilizer amendments can result in revegetation of these tailings dykes and a fair degree of tolerance to natural forces such as torrential rain falls. There is currently no practical technology for reducing the water content of the tailings pond sludge to a level that can return this material to a productive soil state in nature, although mixing with sufficient dry sand could obviously achieve trafficability. With current technology, the most likely fate of the sludge is that it will be left at the bottom of a "natural" water body.

The subject of reclamation and revegetation is further discussed in Section 12.0.

4.5 Alternative Tailings Disposal or Sludge Treatment Technologies

Failure to demonstrate the workability of an environmentally and economically more acceptable reclamation alternative has not been for want of trying. Since the earliest pilot plant work with the hot water process, researchers have been concerned with the resultant tailings problems inherent in the process. There has, however, been a somewhat blind following of the philosophy that the oil sands tailings disposal problem is a "sludge" problem. This attitude, because the sludge was comparable to the slimes from tailings disposal operations for other mining projects, may have resulted in the failure to seriously investigate the possible deposition of both sand and clay minerals together. Thus, solutions which have been proposed for the sludge disposal problem have been chemical or other treatment techniques for the clay sludge alone.

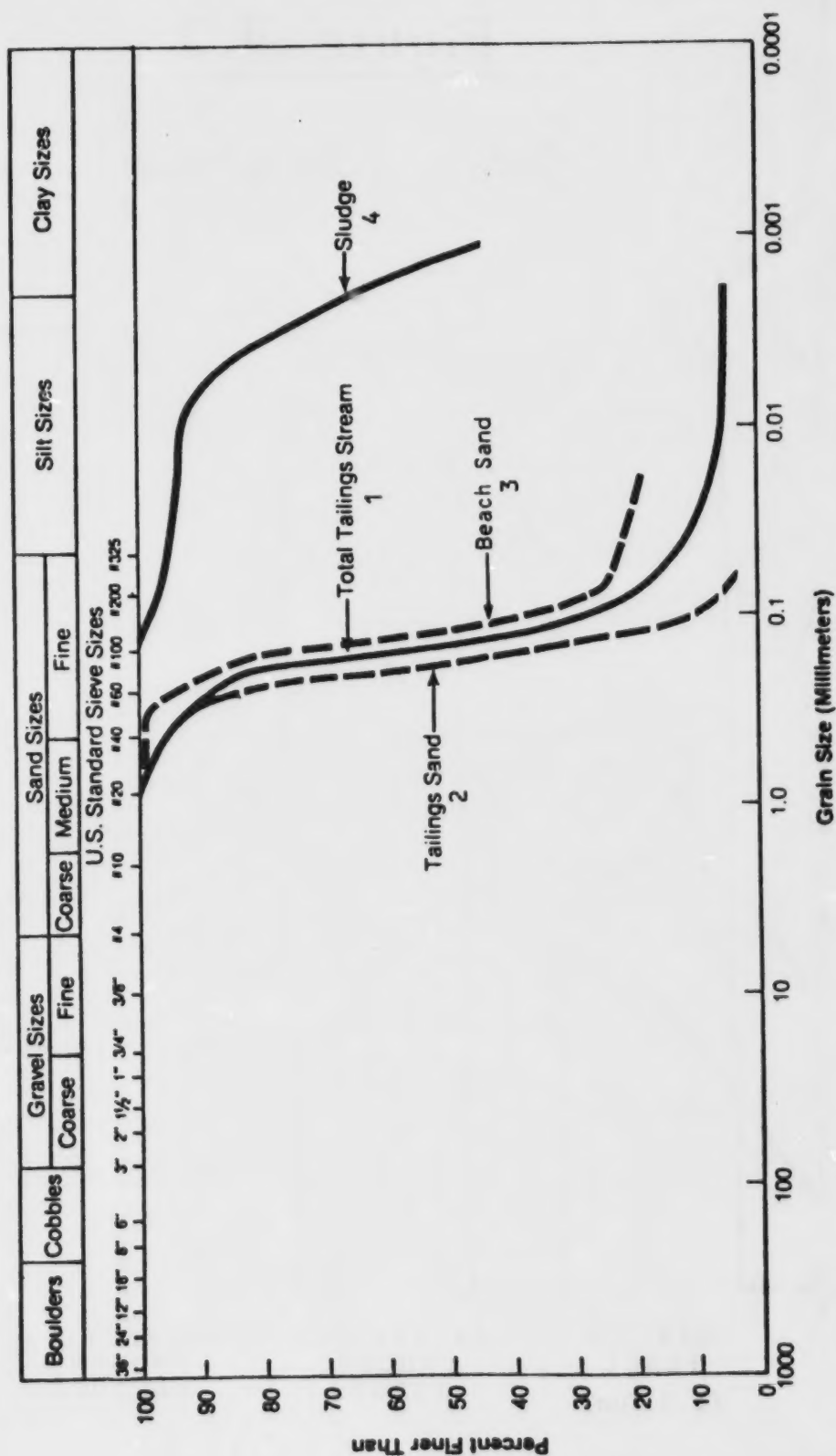
Many of these techniques are definitely effective in reducing the water content of the sludge and improving the properties of the clay minerals for reclamation and revegetation. But so far they have not resulted in a material which is completely satisfactory for these purposes. Examples include the work of Ritter, (1981) on electrophoresis; the work of Joshi (1982) on lime treatment of sludge; and current field scale activity at Suncor on treatment of mixed sludge and sand with starch derived polymeric flocculants (Yong, 1982).

One approach that does not treat sludge alone and has shown considerable promise is the "Thickened Discharge" technique (Robinsky, 1975 and 1978). It is believed this concept has some merit for oil sands tailings disposal. However, it is known to be difficult to obtain a low enough water content for this method on oil sand whole tailings (i.e. it might need perhaps 65 - 70% solids). Such high levels of solids are troublesome for primary separation using hot water technology and would cause severe

(4.12)

erosion problems for tailings pumping and pipelining.

The reader may note that "chemical treatment of whole tailings" has many similarities to the technology championed by Robinsky, with hindered settling being achieved by chemical flocculation/coagulation rather than by lower water levels. The success which has already been achieved with Robinsky's technique will also, hopefully, make it less difficult to commercialize chemical treatment technology.

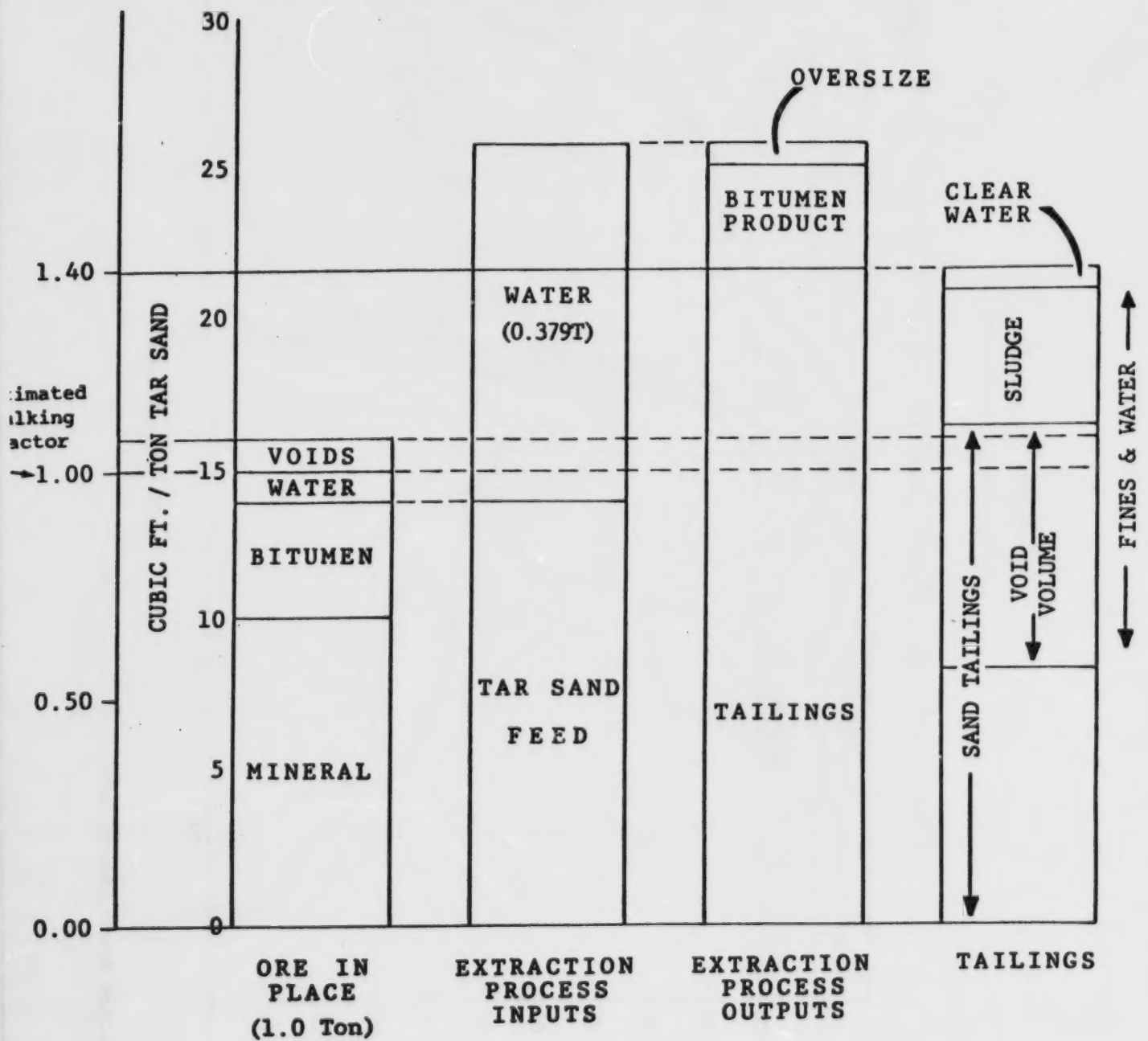
Figure 4.1**Grain-Size Distribution of Oil Sand Tailings**

Modified From: Scott, 1982

(4.14)

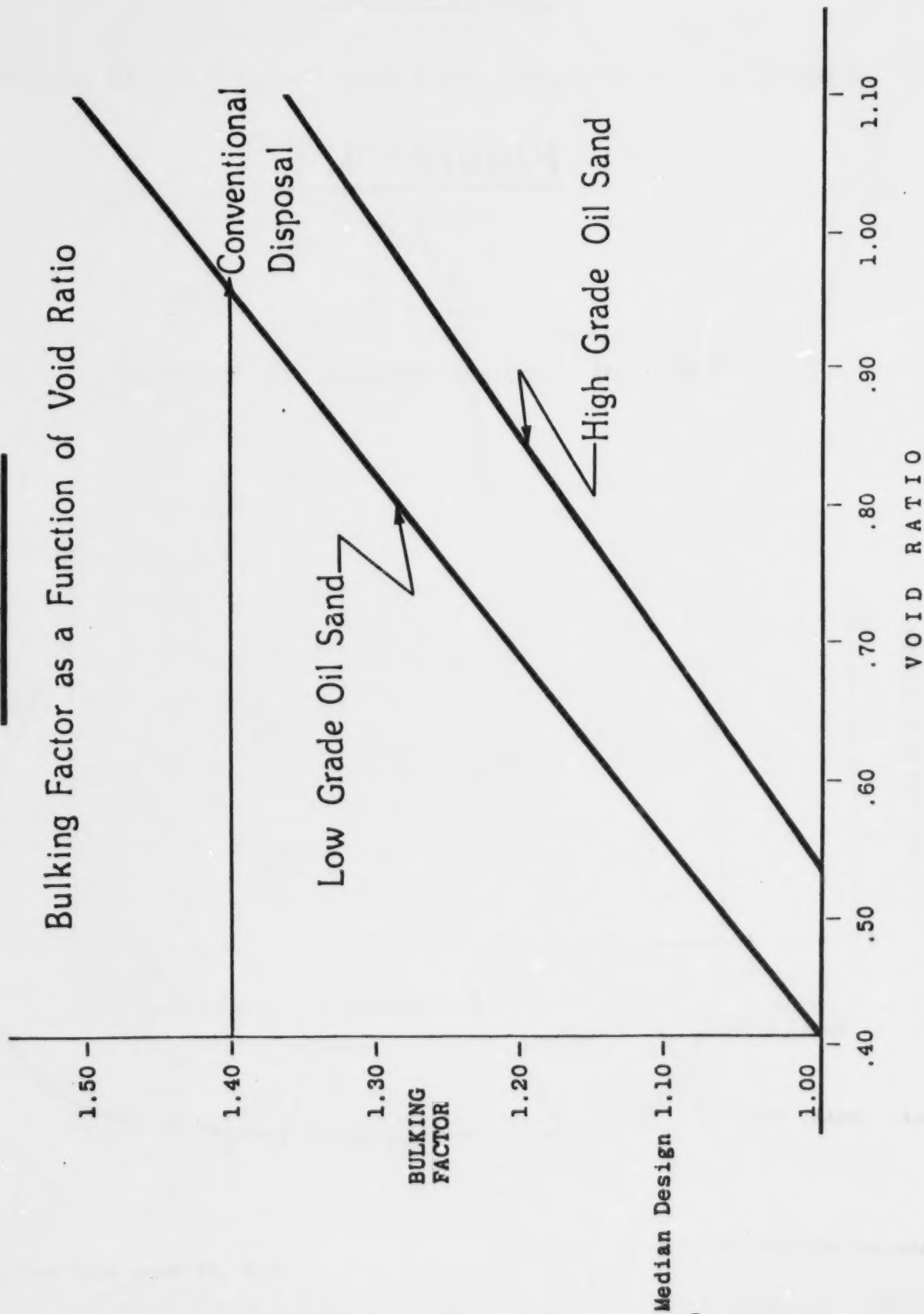
Figure 4.2

Tailings Bulking Factor¹



¹ Modified from Camp, 1976

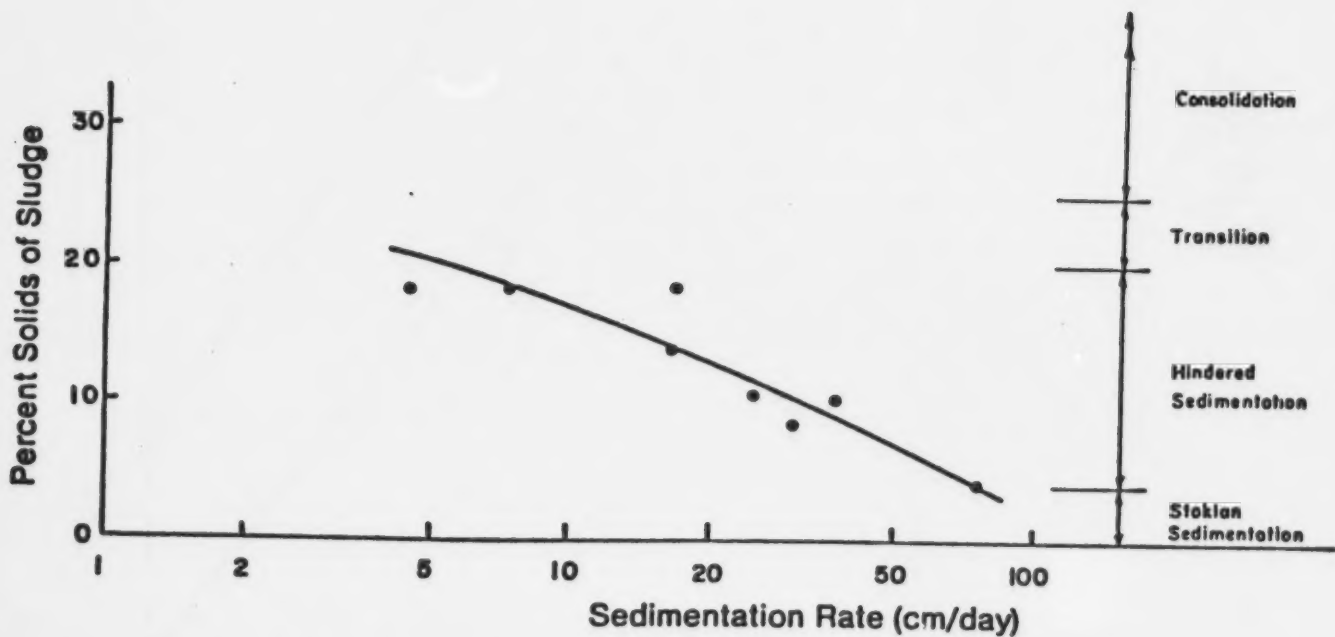
Figure 4.3



(4.16)

Figure 4.4

Rate of Sedimentation of Sludge

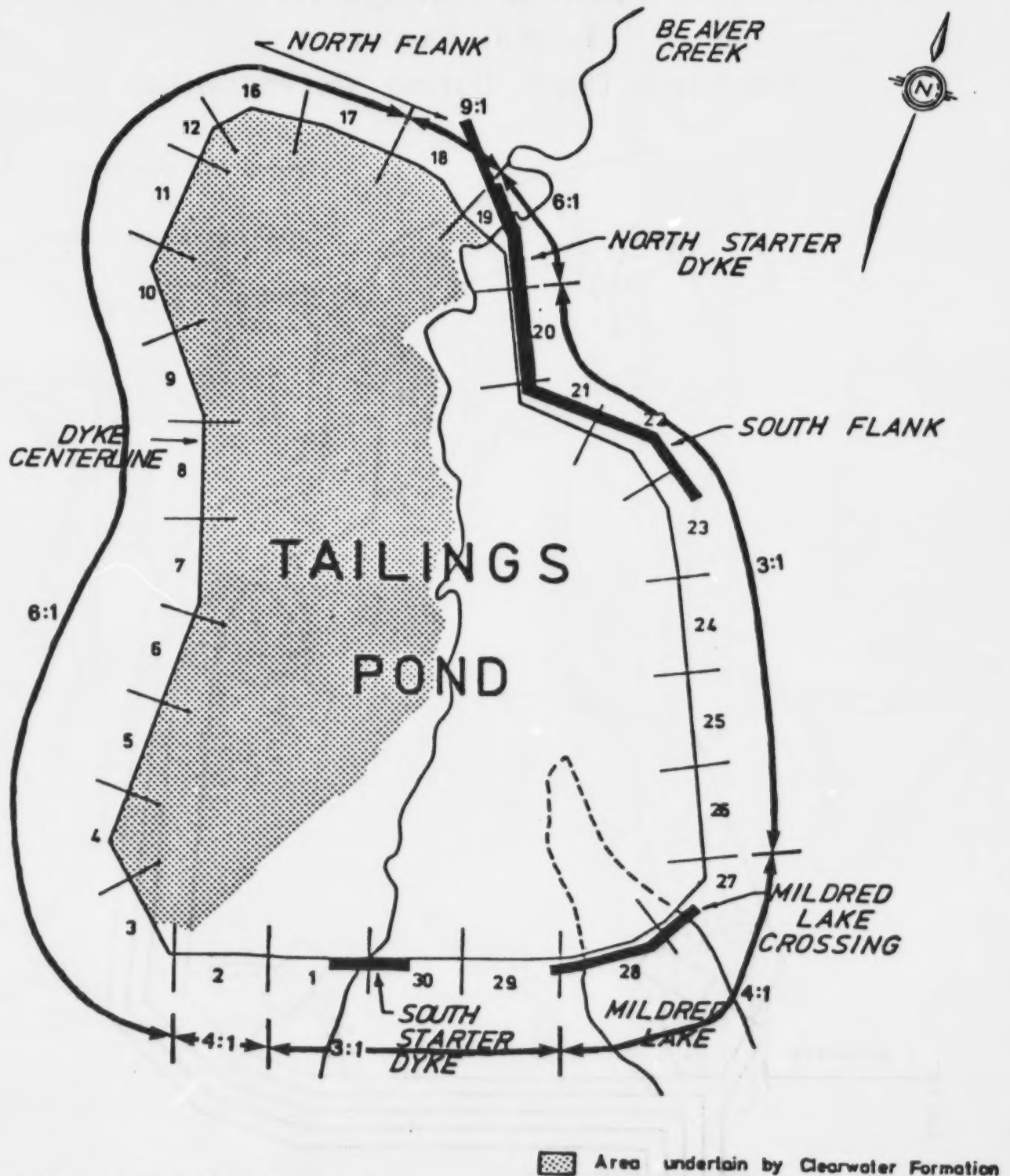


Ref: Scott, 1982

(4.17)

Figure 4.5

General Dyke Layout with Cell Locations and Slopes

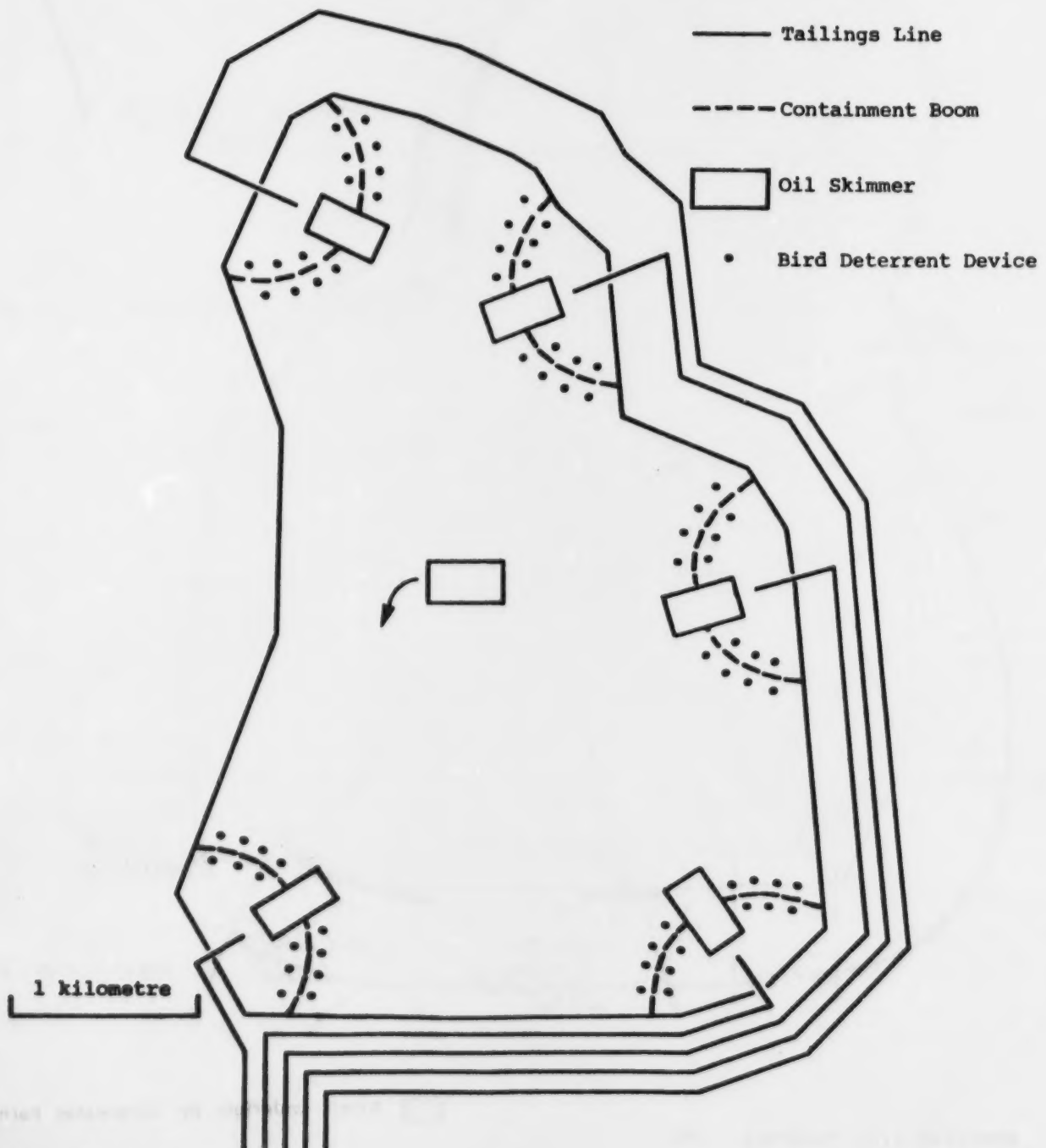


Modified from Handford, 1982

(4.18)

Figure 4.6

Syncrude Tailings Pond Typical Layout of Discharge Lines During Overboarding



Typical Dyke Section

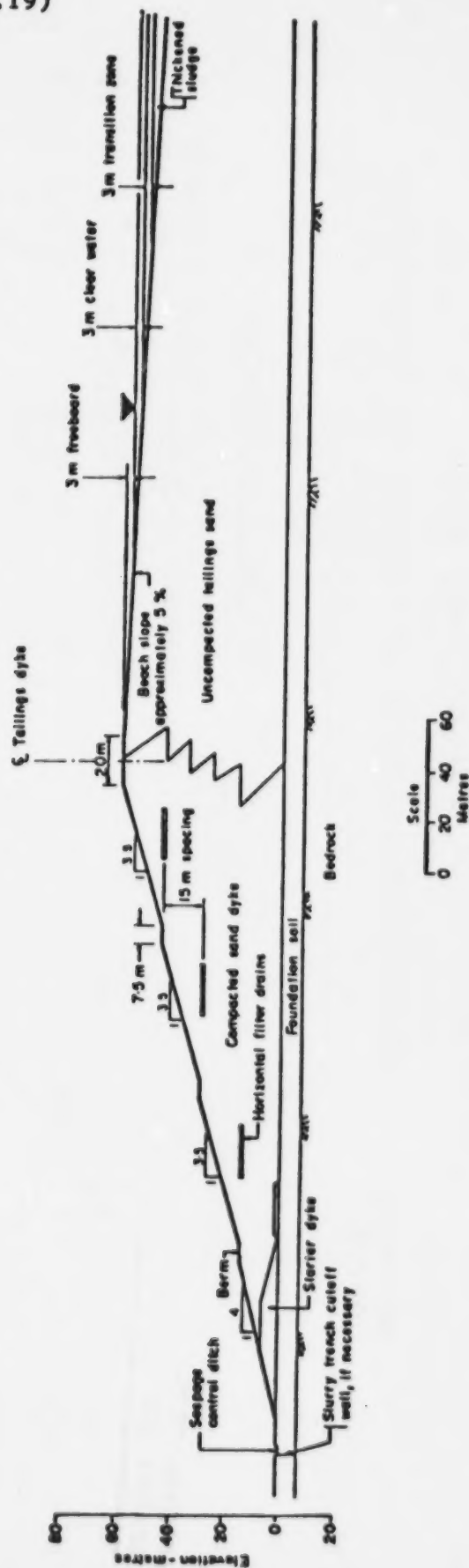
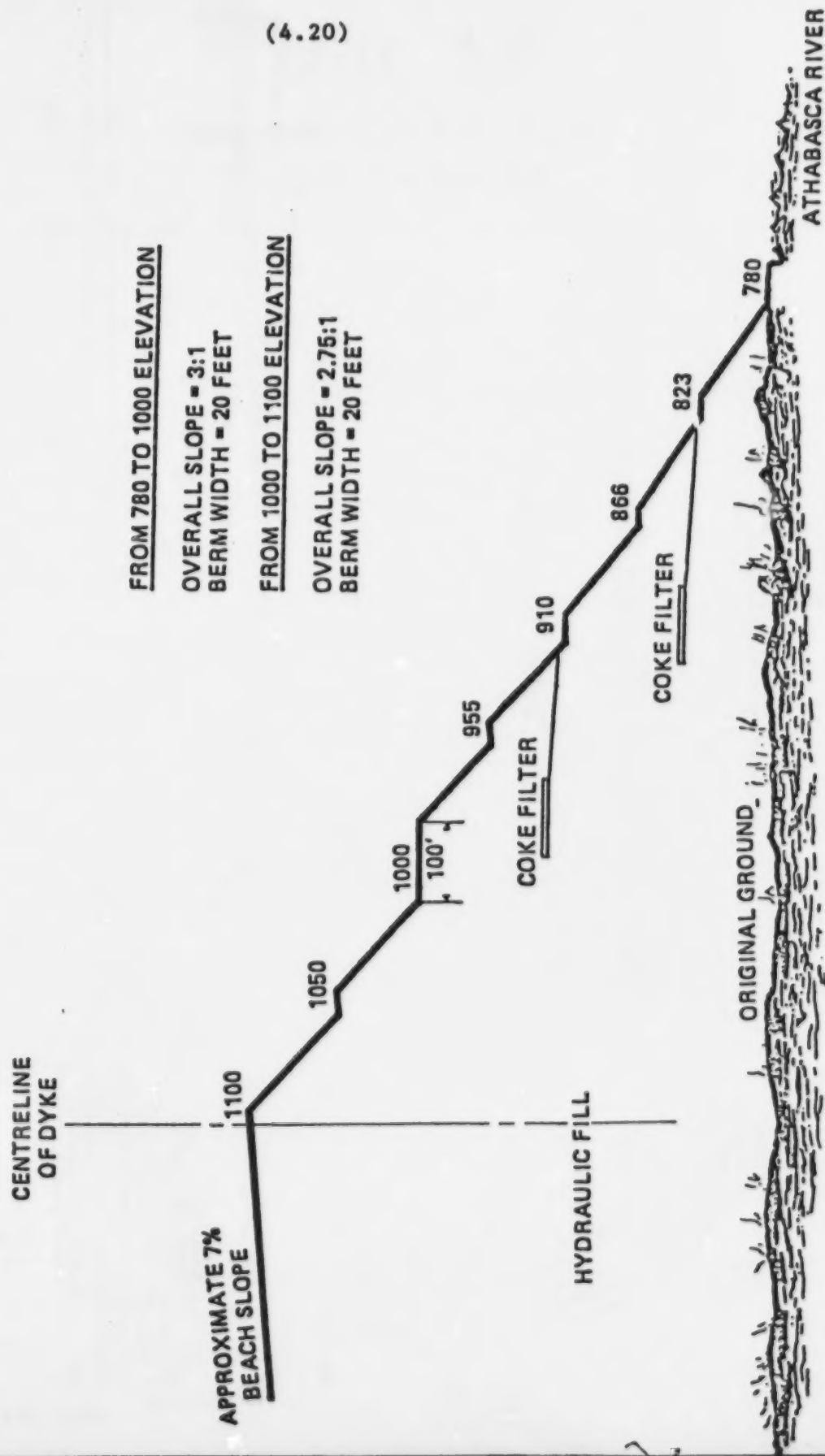


Figure 4.8

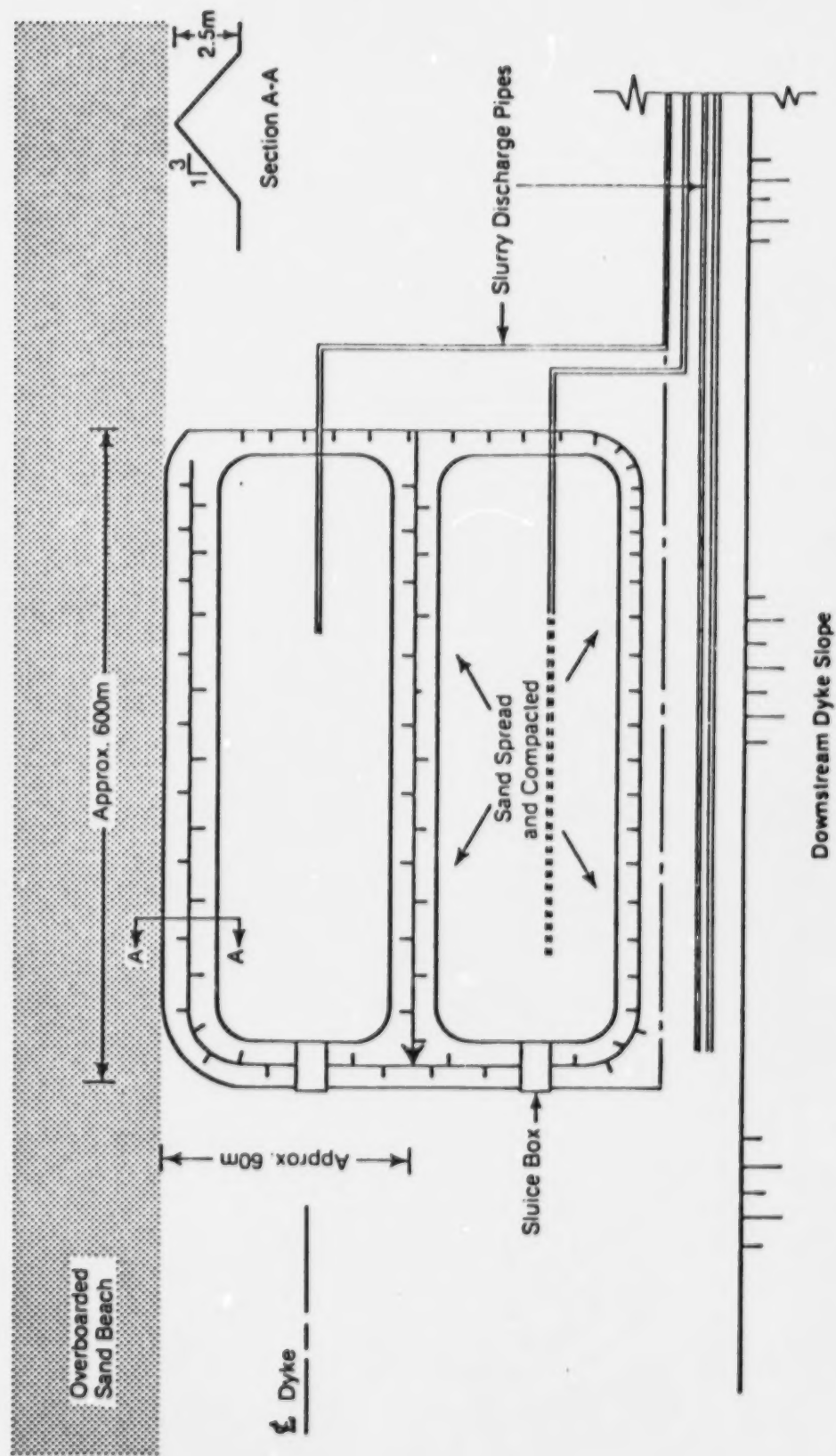
Typical Section of Suncor Sand Dyke



Ref: Humphreys, 1978

Figure 4.9

Hydraulic Dyke Construction





5.0 SLUDGE AND CLAY CHARACTERISTICS

The problems which have been encountered with tailings sludge treatment technologies and the directions in which improved treatment may be obtained can be better understood in light of a discussion of sludge clay properties which are critical to their separation from water.

The key problems with the sludge clays, alluded to earlier, are illustrated in Figures 5.1 and 5.2.

Figure 5.1 shows the low density of the sludge and how even at very high consolidation pressures, the sludge density is still low, (void ratio is high), indicating the sludge is still fluid.

Figure 5.2 shows that the dewatering of the sludge is also greatly hindered by very low sludge permeabilities, which continue to decrease drastically as pressure is applied. At void ratios (or confining pressures) similar to those in Figure 5.1, the sludge permeabilities are so low that the sludge may take literally thousands of years to drain to a solids level that is non-liquefiable.

The sections which follow discuss the characteristics which contribute to these problems: the size and shape of clay minerals, the charge characteristics, how these particles behave in the presence of electrolytes, the effect of bitumen coatings on the particle properties and other relevant factors.

5.1 Clay Mineralogy and Structure

The essential building blocks for clay minerals are silicon-oxygen tetrahedra (Figure 5.3) and aluminium oxygen octahedra (Figure 5.4). Both the tetrahedral and octahedral structures tend to form layers and aggregate in layered "sandwich" structures.

The primary distinction between the different species of clay minerals relates to the way in which these building blocks combine to form laminated or platelet type structures, with a common distinction being made between "1:1" layer clays and "2:1" layer clays. Another distinction is whether or not they are "swelling clays" in which the relative positions of two layers can change due to the absorption of water or other species.

5.1.1 Platelet Structure

The structure of the platelet minerals causes them to exhibit a

(5.2)

much slower settling velocity than would be expected for the overall mass and an assumed spherical dimension of the particle as determined by most sizing methods (i.e. Stokes Law settling where settling velocity is normally assumed to be related to the particle diameter of roughly spherical particles).

Another aspect of this shape and the way the particles are charged which causes problems is the resultant way in which the particles aggregate, which is discussed in more detail in section 5.4.

These platelet shaped particles, if "mobile" also tend to blind pore spaces in soil structures or cause problems with solid-liquid separation equipment which might be used to effect separation from the liquid phase. For example, filtration media can be readily blinded by platelet type clay minerals which can also blind filter precoat materials such as sand or diatomaceous earth.

5.1.2 2:1 Layer Clays (Illite and Montmorillonite)

Both illite, one of the commonest clays seen in oil sand environment and montmorillonite, a clay which is encountered occasionally at levels of 5% or so, are 2:1 layer clays. The "2:1" description indicates that they have an octahedral sheet sandwiched between two tetrahedral sheets as illustrated in Figure 5.5.

Illite is a non-expandable clay, meaning that the relative dimensions in Figure 5.5 are essentially fixed, whereas with montmorillonite, they are not. In particular, the distance between "laminations" of the montmorillonite layers, the "c" dimension indicated in Figure 5.5 is typically from 12.5 to 20 angstroms, depending on a number of factors such as the type of any absorbed cations. (Note the term bentonite, often substituted for montmorillonite, actually refers to a "rock" or "soil", which contains a high proportion of montmorillonite.)

5.1.2.1 Chlorites

Chlorites are a special case of 2:1 layer clays occurring occasionally in oil sand and tailings. In this mineral, montmorillonite type layers are cemented together by a magnesium hydroxide interlayer. The magnesium is usually somewhat substituted by Al^{+++} with the overall result that any cation deficiency of the mineral is almost compensated. Chlorites thus have a much lower degree of surface charge or reactivity with cations in solution than montmorillonite.

5.1.3 Cation Exchange Capacity (C.E.C.)

The swelling property of montmorillonite is due to extensive substitution of the silicon or aluminum atoms in the tetrahedral and octahedral crystal lattices, by lower charged but similar sized metal cations such as Na^+ , K^+ , Mg^{++} and Ca^{++} . This substitution of cations, which tend to be highly mobile in aqueous solution causes charge and particle orientation characteristics which result in the inclusion of a number of layers of water molecules (or perhaps other polar compounds) between adjacent layers of the mineral. With montmorillonite, silicon or aluminum atoms have been replaced at a number of sites on the external surfaces of the clay particles (i.e. many layers thick) as well as sites between crystal layers of the mineral. The result is that montmorillonite typically shows a measurable "cation exchange capacity" of the order of 80 to 150 milliequivalents of cation per 100 grams (meq/100g) of montmorillonite mineral.

Table 5.1 presents the typical range of cation exchange capacities for some common clays which can be present in the oil sand, (all of those indicated except for vermiculite which is typically derived from volcanic sources and rarely found in oil sand).

Cation exchange capacity has proven to be a useful concept for dealing with clays in many situations such as drilling muds and agricultural soils. It has been measured for our material for reclamation purposes (in a separate study for A.E.R.T.) at about 5meq/100g.

5.1.4 1:1 Layer Clays (e.g. Kaolinite)

Figure 5.6 illustrates the general arrangement of atoms and layers of atoms in the 1:1 layer clays such as kaolinite which are non-swelling in water. The other members of the 1:1 layer clay family are dickite, nacrite and halloysite, which differ from kaolinite primarily in the way layers are stacked. Halloysite is unique in that it contains interlayer water one molecule thick. It can also be irreversibly dehydrated by heating to a second form known as metahalloysite (or halloysite 7A, for the 7 angstrom "c" layer thickness. The hydrated form is halloysite 10A).

Kaolinite and the other 1:1 layer clays (except perhaps halloysite) exhibit exchangeable cations only at the surface, (except in the presence of so-called "intercalating" polar organics such as urea) and, as such, typically show much lower CEC's than montmorillonite, lower even than most 2:1 layer clays.

In general, it can be said that the magnitude of the CEC is inversely related to the number of silicon and/or aluminum atoms which are deficient in the crystal lattice (or occupied by lower

valence cations which can be readily displaced from their crystal positions, the exchange sites).

5.2 Particle Charge Characteristics

As mentioned previously, clays and other silica or alumina minerals, especially in contact with water, tend to have a significant number of Si^{++++} or Al^{+++} ions missing from the crystal lattices or substituted with lower valence species such as Na^+ , K^+ or Ca^{++} . The result of these two factors is that virtually all clay minerals are negatively charged when they are suspended in water.

As well, the broken edges of crystals at a particle surface where ion charges are not completely compensated (as they are in the interior of the minerals), tends to result in negatively charged clay particle surfaces (uncompensated oxygen atoms), and positively charged edges (uncompensated silicon or aluminum ions).

5.2.1 The Double Layer

Negatively charged particles, carrying such a charge for either or both of the reasons mentioned, tend to collect a layer of cations immediately around them in solution. This layer is attracted by the excess particle negative charge, as illustrated in Figure 5.7. The solution layer immediately surrounding the particle thus becomes positively charged. Negative ions, drawn by this positive layer, collect in the layer immediately next to the cation layer to balance the positive charge. This second "anion" layer, because it is larger in volume, tends to be somewhat less concentrated than the cation layer immediately adjacent to the particle. It also tends to have a radially outwards declining ionic concentration, eventually indistinguishable from the bulk of the solution some distance from the particle surface.

This collection of ions, results in a particle which still appears to be negative to the solution, though much larger in diameter. The fluid envelope is usually referred to as the "double-layer," illustrated in Figure 5.7. A knowledge of the behaviour of this double layer serves to explain many of the aspects of particle behaviour in solution and their interactions with various charged species.

The nature of this double layer is, however, affected by many factors such as the concentration of electrolytes. The knowledge of its existence has been found to have somewhat limited utility since measurement of its shape or nature is difficult.

What is probably more useful for practical purposes is a relatively simple means of determining whether or not a particle is charged and by how much. The concept of "zeta potential" serves this purpose.

5.2.2 Zeta Potential

When negatively charged particles are exposed to an electrical gradient between electrodes in an aqueous solution, they begin to migrate at a rate which depends on their charge in the direction of the positive electrode. This property has been utilized in the construction of a so-called "zeta meter" to measure the charge on particles in solution. The interpretation of what the rate of particle movement means in terms of charge density is complicated by such factors as the variable size of the associated double layers of solution ions. However, the "zeta potential" (Z.P.) concept has been developed into a useful standard for determining the extent to which particles will attract or repel each other, based on the individual characteristics of the particles.

Figure 5.8 illustrates the common relationship between particle size and zeta potential. In the case of silica illustrated, the surface charge is due primarily to broken bonds at the particle surface. These are more significant on the smaller particles which have much higher relative ratios of surface to interior crystal than do the larger particles.

Table 5.2 summarizes the relationship between zeta potential and particle aggregation or disassociation. Particles of all types are most aggregated at zero Z.P. and least aggregated at the most highly charged Z.P.'s of Z.P.'s such as minus 60 microvolts or less. Clays in oil sands tailings typically show Z.P.'s approaching the -60mV level.

Figure 5.9 shows the influence of electrolytes on the particle surface charge. From the Figure the addition of sodium hydroxide (NaOH) and some other sodium salts would tend to act as a dispersant for the oil sands clays in the extraction process. They do, and this characteristic improves bitumen extraction efficiency. However the charge on the particles due to NaOH is actually very effective at preventing proper settling of clays and fines in the tailings pond.

While particle charges are somewhat intrinsic, as mentioned, due to cation deficiencies, addition of NaOH (or other solubilizing agents) to a solid suspension can preferentially dissolve species such as Al^{+++} or Si^{++++} and result in even more highly charged particles. This has, in fact, been observed for the primary clay species in the oil sands, kaolinite and illite.

(5.6)

Due to cation deficiencies in the mineral crystals, absorption and layer effects and other factors, the exchange process is not stoichiometric.

Displacement of Na^+ by Ca^{++} , for example, may be significantly less than would be expected based on the uptake of Ca^{++} by the clay minerals and the amount of exchangeable Na^+ known to be present in the clay.

When charged particles are exposed to high charge density cations in solution, the charge deficiency can be compensated and the zeta potential reduced, as evident in Figure 5.9 with Al^{+++} , Fe^{+++} , or Ca^{++} coagulants. However, for several reasons (to be discussed) related to particle size, shape and charge distribution, simply neutralizing the particle charges and coagulating the clays (as is done in potable water treatment) is unlikely to be effective in settling and dewatering oil sands clay sludges by themselves.

5.3 Bitumen Coating of Clays

A phenomenon which also causes problems in oil sands tailings sludge disposal is the presence of a bitumen coating of some clay particles, which, if it occurs, tends to slow the settling rate and increase the compacted volume of sludge material. It was illustrated in Figures 5.1 and 5.2. While it is difficult to remove the bitumen coating from these particles without also influencing other properties of the minerals such as the cation exchange state, it is clear that an organic coating will increase the volume and reduce the attainable bulk density of the sludge particles, as bitumen has essentially the same density as water. Obviously, a lot of bitumen in the tailings is also an extraction efficiency problem, which, it is believed, should be dealt with in the extraction plant.

Calcium rich clays tend to be self coagulating and to have a "cohesive" rather than a "dispersive" nature in a wet environment (terminology as used by geotechnical engineers). Some of the key reclamation and revegetation properties of the material which depend on the cation exchange capacity of the clay soil are also significant for permanent tailings disposal, since revegetation is essential to prevent catastrophic erosion.

5.4 Coagulation of Clay Fines

From Table 5.2 and Figure 5.9 illustrating the effect of multivalent cations, the reader can appreciate the rationale behind water treatment coagulation with multivalent cationic

species such as Al^{+++} , Fe^{+++} , and Ca^{++} .

The influence of these cations on fine particles in an aqueous phase is the basis for clay removal for potable water treatment or water treatment "coagulation". In this process lime (CaO), ferric chloride ($FeCl_3$) or alum ($Al_2(SO_4)_3$) is used to coagulate and settle the natural clay solids present in many rivers and streams used for potable water.

5.4.1 Modes of Particle Association in Coagulation

Clay particles as discussed earlier, are composed of hexagonally shaped plate-like particles which in an aqueous suspension can theoretically associate in three different orientations:

Face-to-Face (FF)
Edge-to-Face (EF)
Edge-to-Edge (EE)

These three modes of particle association, are illustrated in the line drawing of Figure 5.10. The frequency of occurrence of these three types of association in practice are greatly influenced by the exact particle shapes, and the positive end charge and negative surface charge of the clay particles.

The extent to which any or all of these mechanisms occur is also a complex function of the percent solids in solution, the electrolyte strength and the fluid mechanics of the solution movement.

The properties of clay particle solutions and clays deposited from solution such as bulk density and permeability are highly dependent on the particle arrangements (the extent of FF, EF or EE aggregation).

5.4.1.1 Face to Face Aggregation

Face-to-face particle association (FF) results in the effective formation of, larger particles than those that were originally present in solution. Particle size measurements of such aggregates could not likely distinguish an aggregation of fine clays from inherently larger particles which may also be present. The behaviour of the particle system would also be what would be expected of larger particle sizes. Even by microscopic techniques, it may be impossible to distinguish such aggregates from layered clay particles.

However, this type of coagulation, due to the nature of the double

layer, the shape and charge of clay particles and the manner of movement of particles in solution, is relatively rare and very difficult to obtain deliberately.

5.4.1.2 Edge to Edge Aggregation

Edge-to-edge (EE) flocculation, difficult to achieve due to charge repulsion similar to face-to-face, is also an uncommon occurrence in natural systems. The use of anionic polymers which are capable of lying along the edges of two different particles, as illustrated in Figure 5.12, thereby "hinging" them together, can greatly increase the tendency of clays to aggregate in this fashion. Improving this type of mechanism would certainly be a major reason for using polymers in flocculating clay particles.

5.4.1.3 Edge to Face Aggregation

Edge-to-face (EF) flocculation, due to the particle shapes and opposite charge attraction, is by far the most predominant mechanism by which clay particles would normally aggregate. This is also influenced by the fluid dynamics by which the particles collide, which will almost certainly tend to cause the opposite charged edges and faces to adhere to each other. This aggregation mode often causes major problems in dewatering of clay fines since the void spaces in the edge-to-face particle arrangement can contain significant amounts of water. This orientation is often called the "cardhouse" structure; it is illustrated in Figure 5.11. It can have a very high water content and be essentially incompressible.

Although changes in electrolytes, percent solids in solution and the presence of polymers can affect the type of coagulation which occurs in clay systems, in practice it has proven to be extremely difficult with any type of chemical treatment to reduce the water content of clay sludges from the oil sands to below 70%. The most efficient type of chemical treatment that is possible, is thus probably limited to a maximum of perhaps 35% solids concentration unless it can somehow produce a different mode of association than EF or greatly improve the rate of movement of water through the aggregation of very fine particles.

5.5 Coagulation and Flocculation

The concepts of coagulation and flocculation are frequently used interchangeably; they are similar but there are distinctions. Both coagulation and flocculation result in the aggregation of solid

particles suspended in water.

The coagulation process is clearly that brought about simply by the change in surface characteristics of the particles, usually due to a change in solution electrolyte strength.

Flocculation derives from the French word "floccule" which means "wool-like" referring to the texture of the particle aggregation. While flocculation behaviour can also be influenced by changes in solution electrolyte concentration, it is most often due to the action of polymers causing particle aggregation with the polymer "roping" the particles together.

The processes of coagulation and flocculation are by no means mutually exclusive, and it is possible to obtain coagulation with inorganic chemicals and flocculation by organic polymers at the same time. In fact, for many purposes, a combination of organic and inorganic chemicals may give the maximum efficiency for the separation of the solids from the liquid. Figure 5.12 illustrates one such method by which polymers may link clay particles together.

The deliberate addition of very small amounts of polyelectrolytes to tenacious suspensions containing some coagulating salt often yields flocs which are much easier to separate than those obtained by salt coagulation alone. In such applications the polyelectrolyte is called a "coagulant aid". These polymers are often used to treat "slimes" containing clays, for example, slimes from mining operations or slimes in waste-water treatment plants. The polyelectrolyte flocculated system often has improved sedimentation and filtration properties. The mechanism probably relates to the illustration of Figure 5.12.

The resultant settled and drained material can have higher density and higher permeability simultaneously.

5.5.2 Polymers as Soil Conditioners

Polyelectrolytes may be used to keep soils in the proper flocculated condition required for root growth and drainage. In this application, the polyelectrolytes are referred to as soil conditioners. Although the same effect can sometimes be obtained by inorganic agents such as gypsum for treatment of soil, polymeric soil conditioners are not easily washed out by rain water, since they are strongly absorbed on the clay surface. However, despite their greater permanence as well as the small amounts required, their use still seems to be limited because of their comparatively high price. As with other flocculants in a solution, soil conditioners are most effective if they are thoroughly worked into an aerated soil.

5.6 Chemical Treatment of Sludge Alone

Probably one of the most comprehensive reviews of various chemical treatments of clay sludge which has been published was the Specken, 1978 report on clarification of sludge containing oil and wastewaters.

While sludge clays can be fairly easily coagulated or flocculated, due to the solids concentration limitations discussed earlier and the huge volumes produced in oil sands operations, dewatering to the point where sludge can be reclaimed and revegetated has proven to be too expensive to be economically feasible.

While the variable response of clays to treatment techniques makes it somewhat difficult to prove conclusively, the authors believe that it is unlikely that any treatment of sludge alone could economically produce a trafficable soil for revegetation (which we believe should be the ultimate objective).

Taking our inspiration from the arrangement of sand and clay of the oil sand in situ, we have sought a way of reconstructing the original structure of the oil sand, illustrated in Figure 2.4 (minus the bitumen).

As has been demonstrated, (Liu, 1980) the co-precipitation and co-deposition of sand and clay can be achieved by a variety of water treatment coagulants with multivalent cations: $\text{Al}_2(\text{SO}_4)_3$, FeCl_3 and others have been tried and work reasonably well.

Figure 5.12 compared the coagulation and settling which can be achieved with lime (or these other coagulants), to untreated tailings.

Lime (CaO) has a number of characteristics which distinguish it from these other coagulants. One of the major factors is the ability to react with sand and clay to cause "stabilization" or strengthening of the soil as well as improved permeability. It is anticipated that improved strength and soil permeability could be very useful characteristics for engineering tailings disposal systems.

Section 6.0 (following) provides a brief background in the science of lime stabilization and the art of "soil modification."

Figure 5.1

Consolidation of Sludge

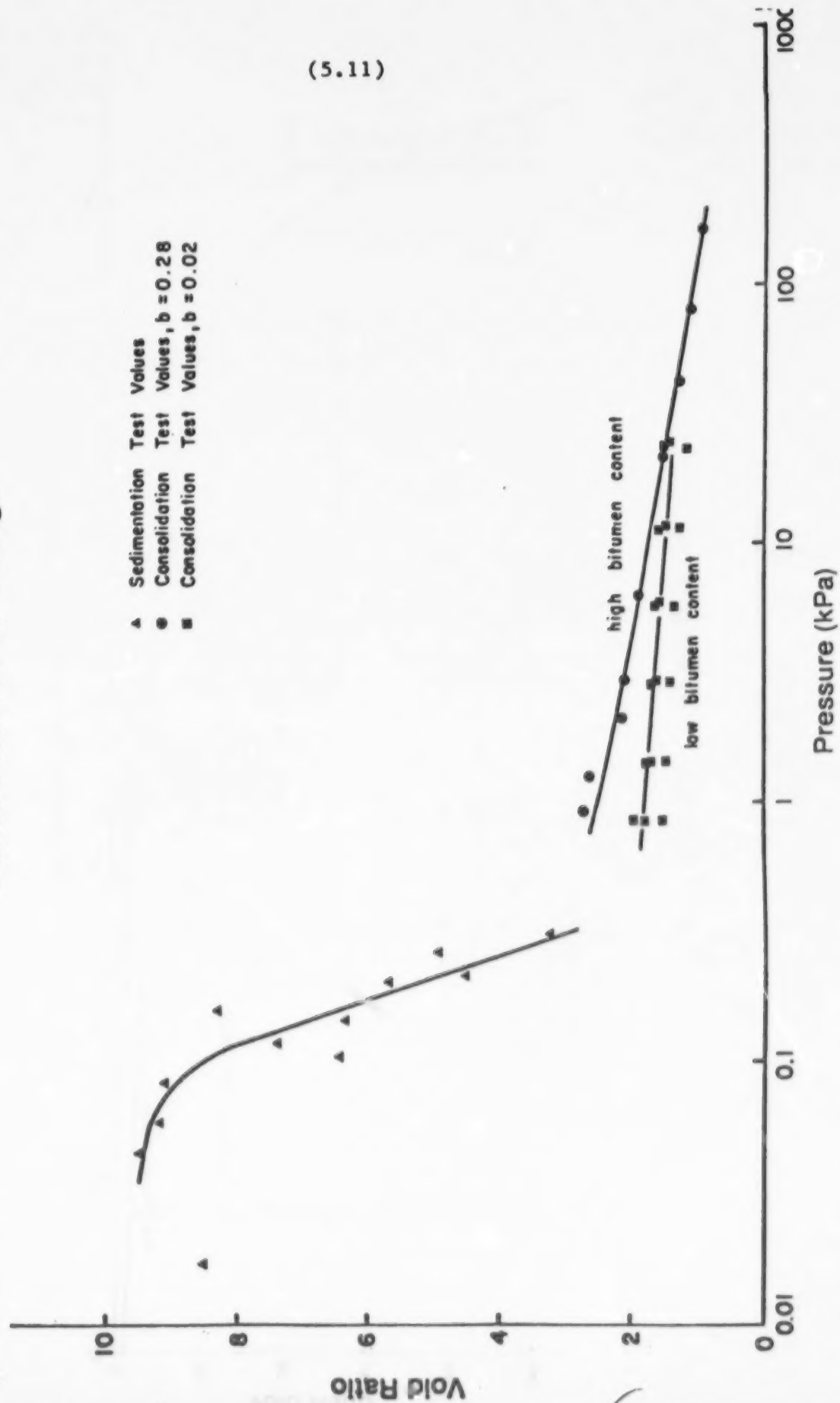
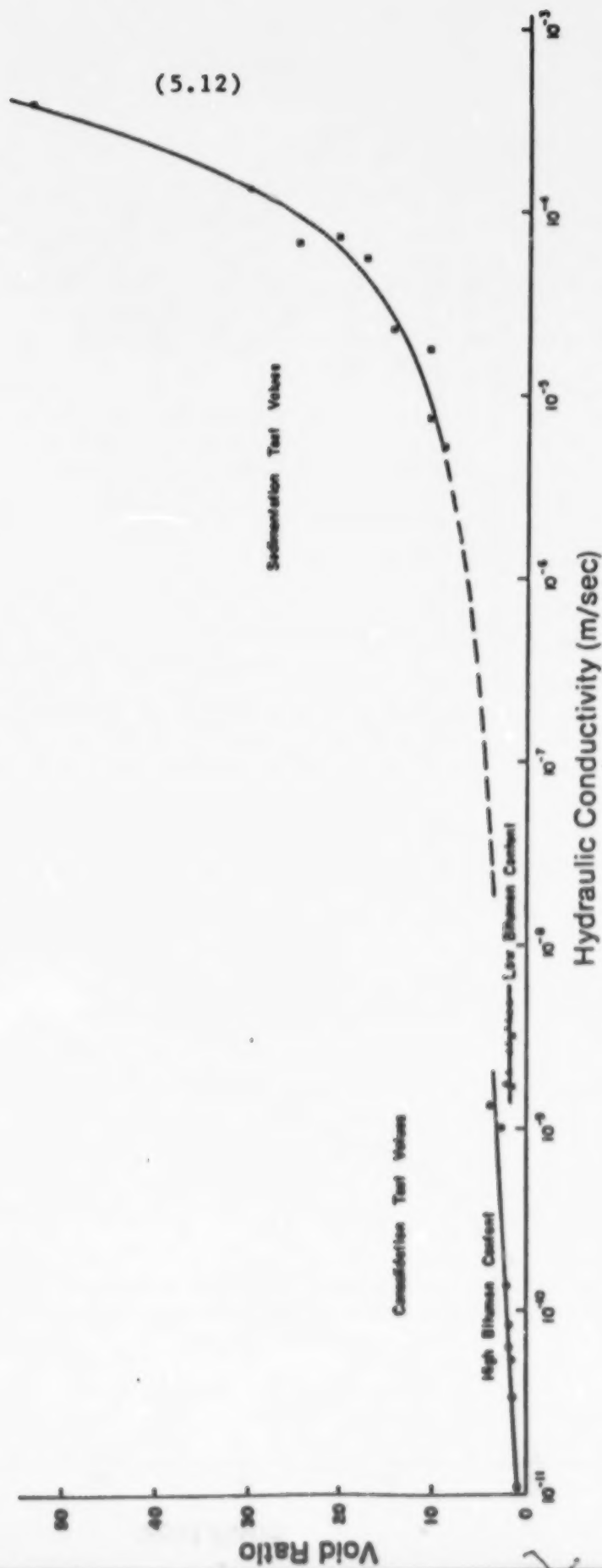


Figure 5.2

Sludge Permeability

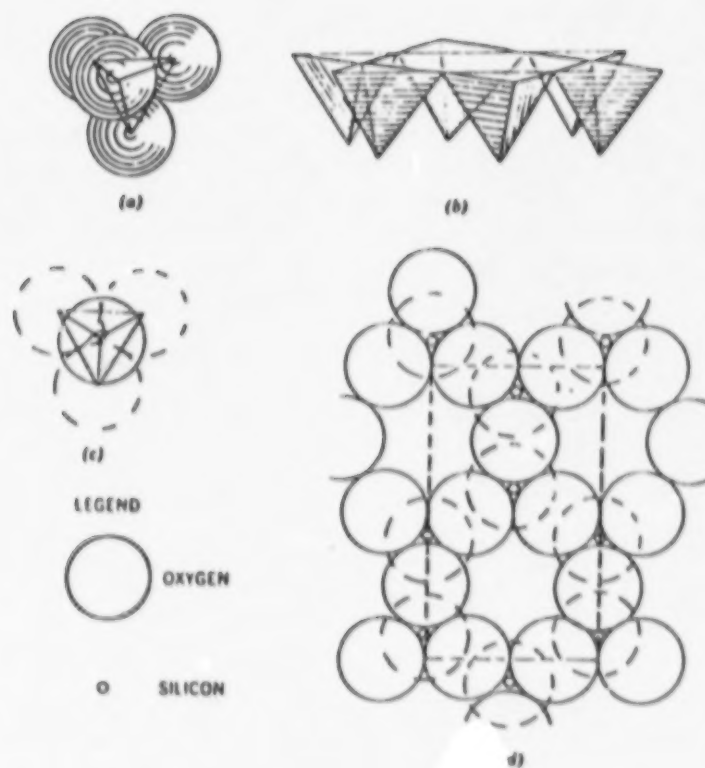


Ref: Scott, 1982

(5.13)

Figure 5.3

Silica Tetrahedra

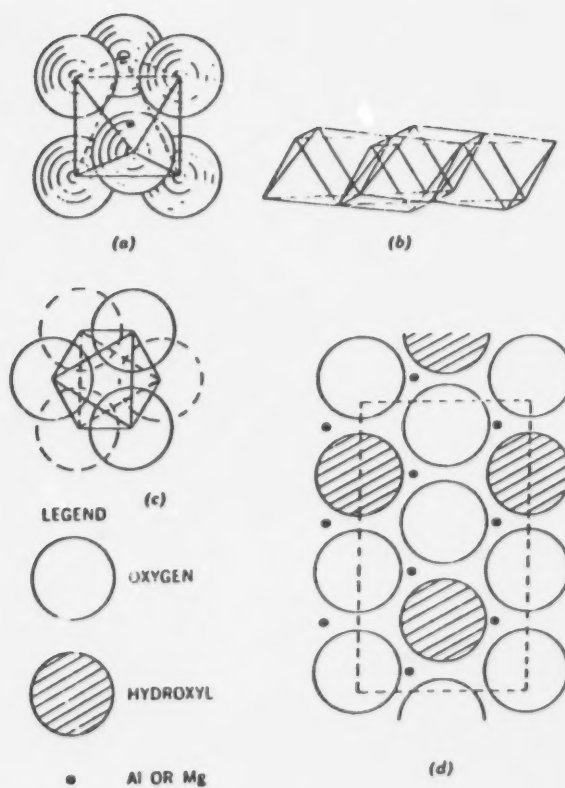


Ref: van Olphen, 1977

(5.14)

Figure 5.4

Alumina or Magnesia Octahedra

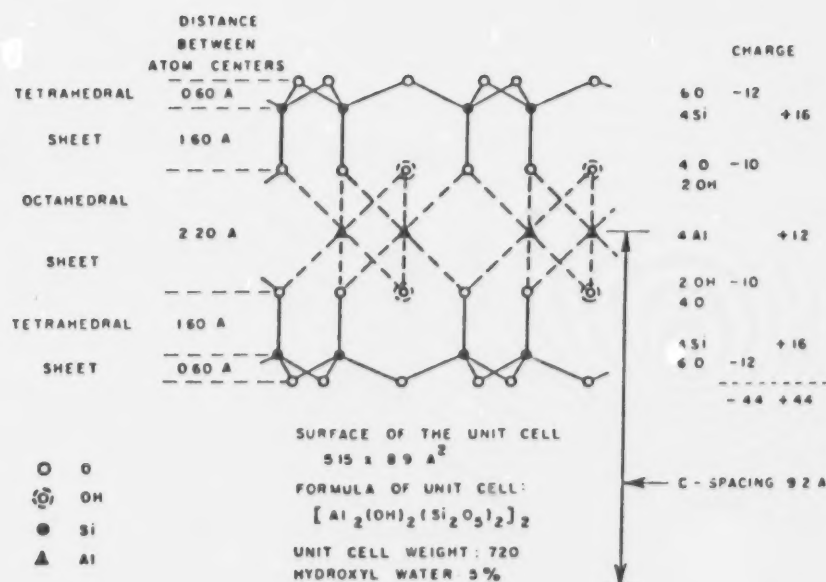


Ref: van Olphen, 1977

(5.15)

Figure 5.5

Atomic Arrangements in a 2:1 Layer Clay (Such as Illite)

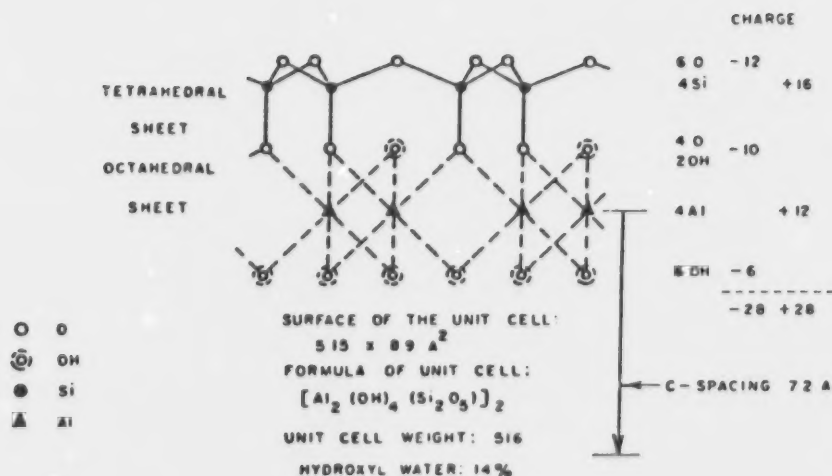


Ref: van Olphen, 1977

(5.16)

Figure 5.6

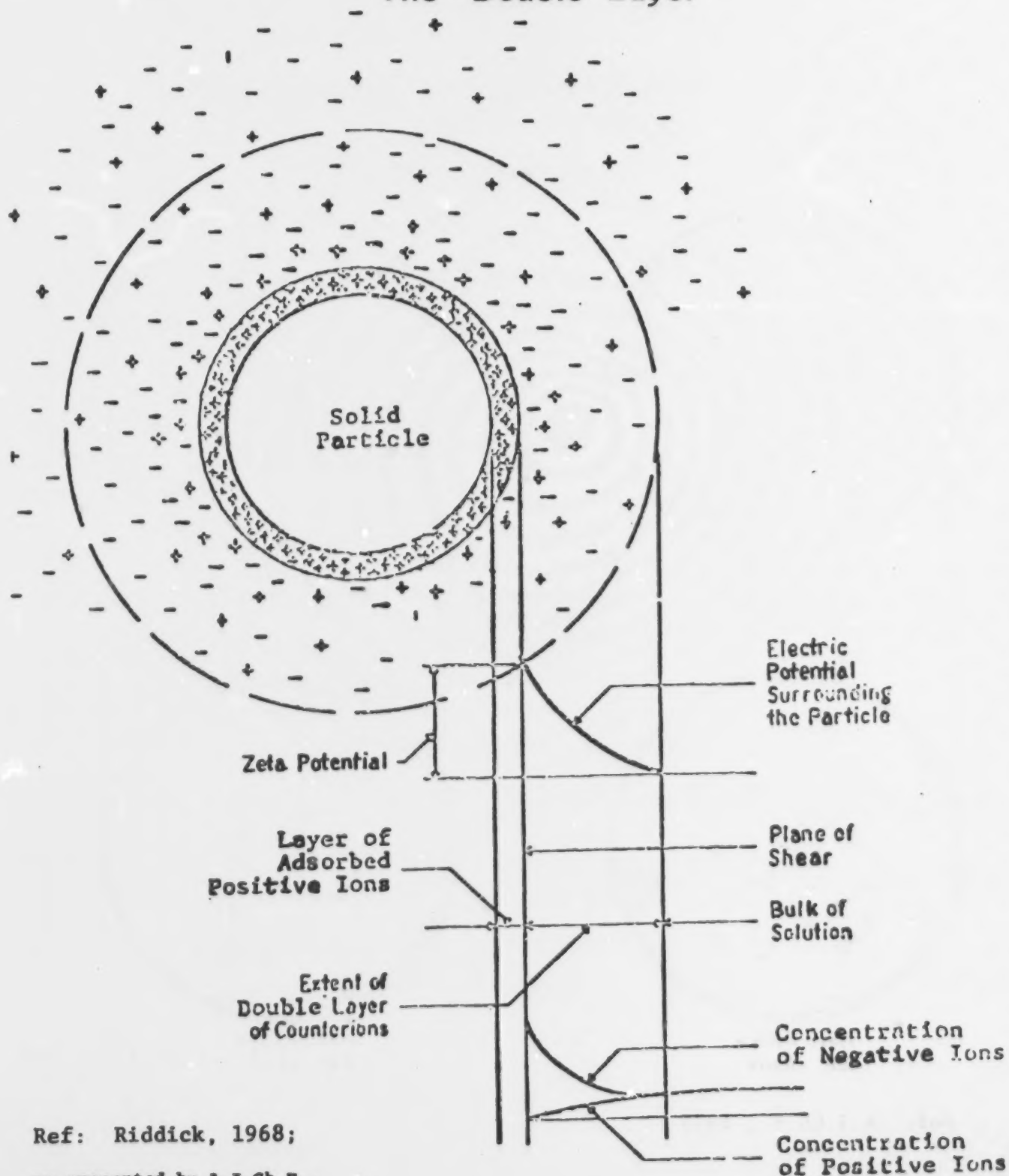
Atomic Arrangements in a 1:1 Layer Clay (Such as Kaolinite)



Ref: Van Olphen, 1977

Figure 5.7

The "Double Layer"



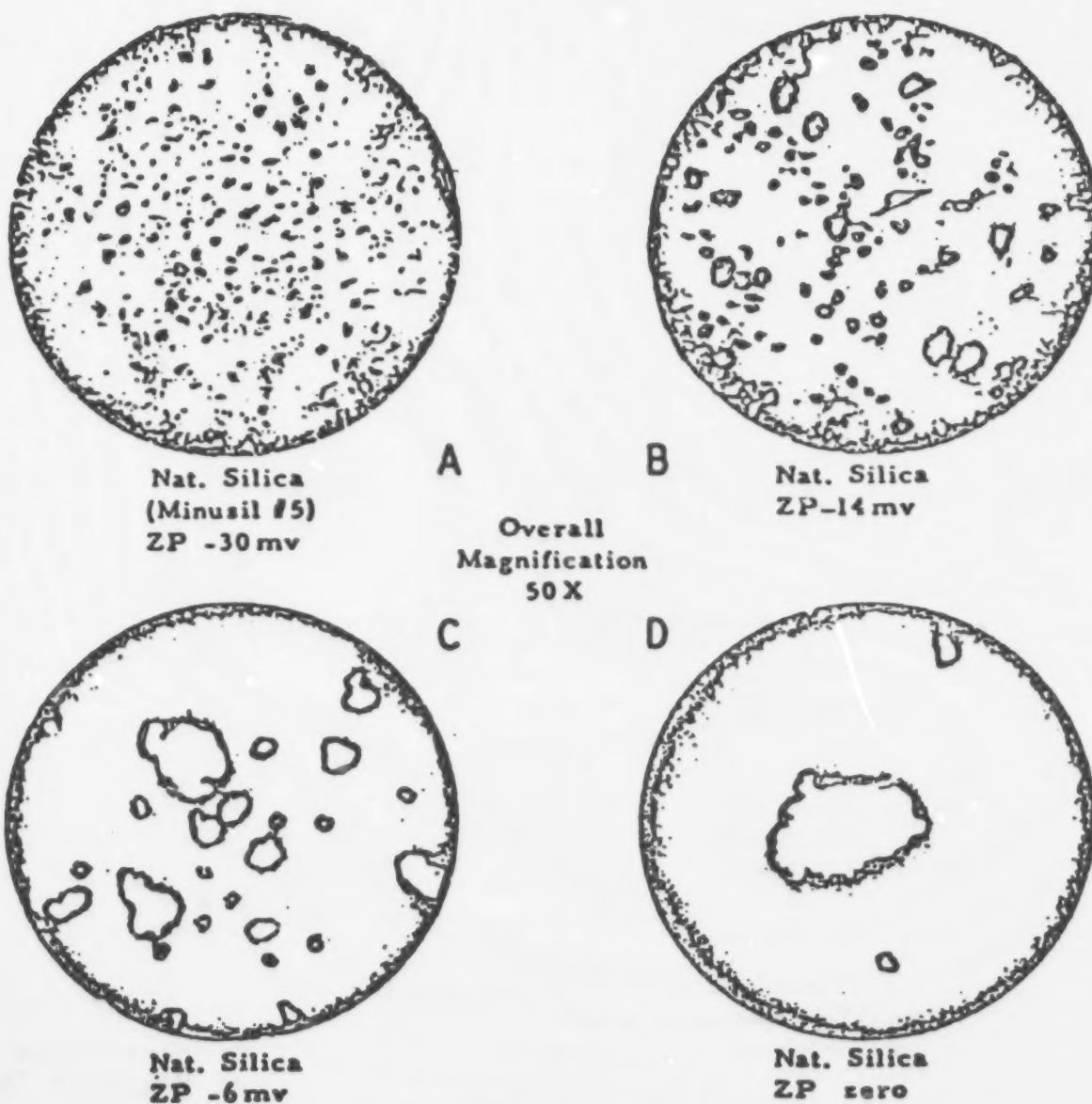
Ref: Riddick, 1968;

as presented by A.I.Ch.E.,
1975

(5.18)

Figure 5.8

RELATIONSHIP BETWEEN PARTICLE SIZE AND ZETA POTENTIAL



Ref: A.I.Ch.E., 1975

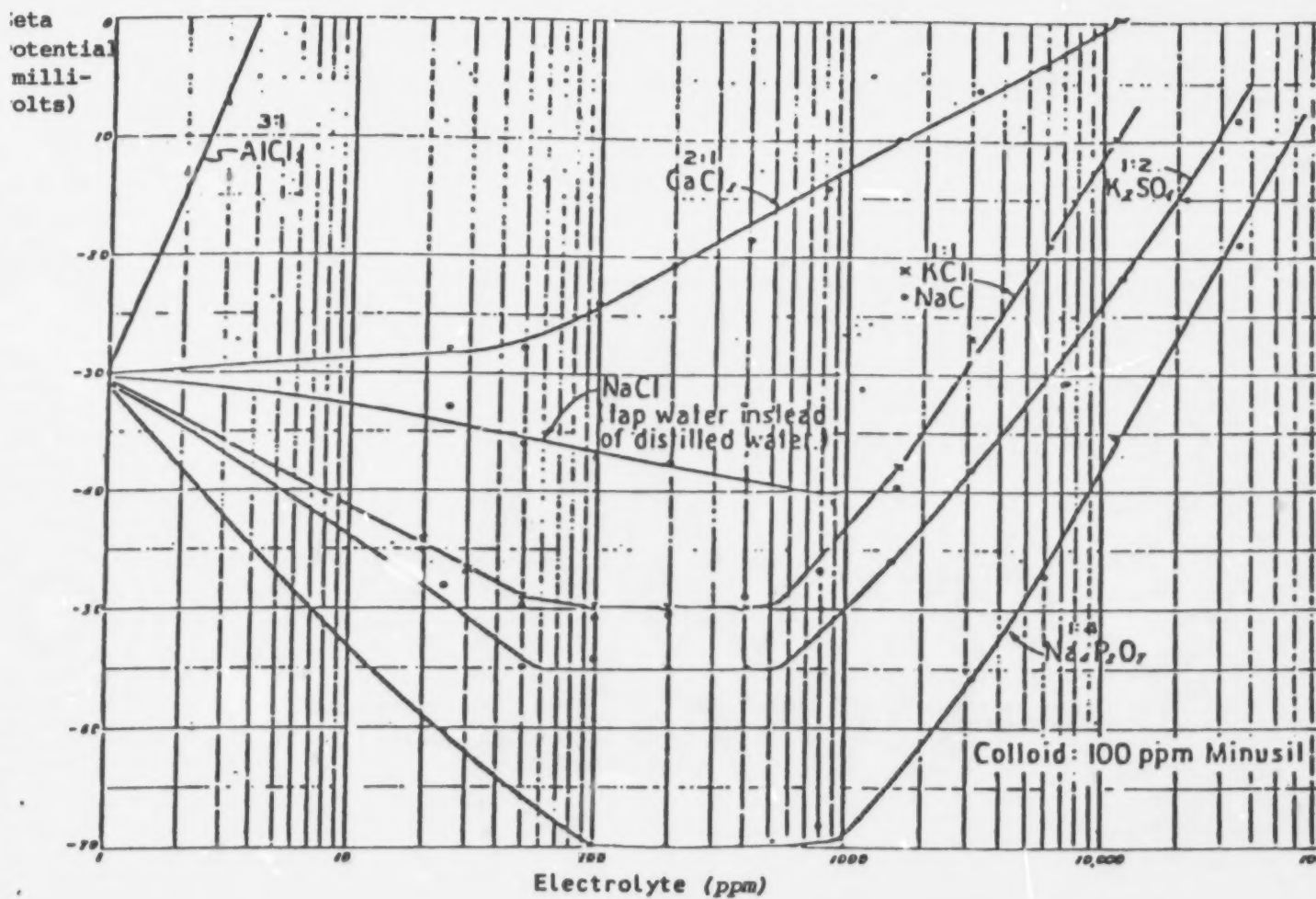
(5.19)

Figure 5.9

EFFECT OF CONCENTRATION OF ELECTROLYTE (P P M)

ON

ZETA POTENTIAL (MILLIVOLTS)

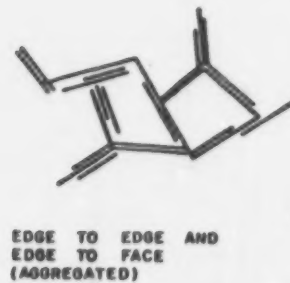
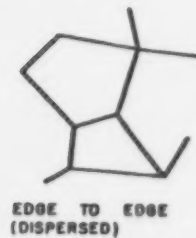
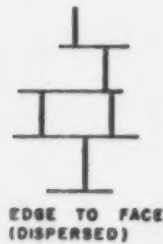


Ref: A.I.Ch.E., 1975

(5.20)

Figure 5.10

Modes of Clay Particle Association



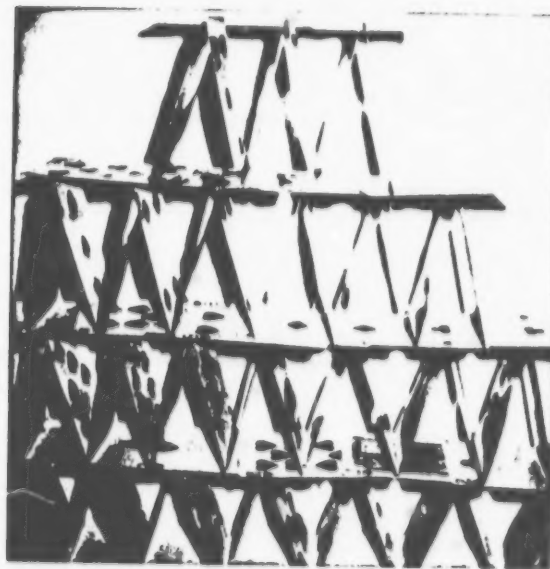
Ref: van Olphen, 1977

(5.21)

Figure 5.11

The "Cardhouse" Structure

- illustrating the result of platey particles with negative surfaces and positively charged edges coagulating.



(5.22)

Figure 5.12

Effect of Polymer as a Coagulant Aid



THE SUSPENSION IS STILL
AGGLOMERATED OWING TO
THE POLYANION LINK

Ref: van Olphen, 1977

(5.23)

TABLE 5.1

TYPICAL CATION EXCHANGE CAPACITY OF VARIOUS TYPES OF CLAY

Type of Clay	Cation Exchange Capacity	
	meq/100 g	meq/g
1:1 Layer Clays		
Kaolinite	3 - 15	.03 - .15
Halloysite	5 - 50	.05 - .5
2:1 Layer Clays		
Chlorite	10 - 40	.1 - .4
Illite	10 - 40	.1 - .4
Montmorillonite	80 - 150	.8 - 1.5
Vermiculite	100 - 150	1 - 1.5

(5.24)

T A B L E 5.2

RELATIONSHIP BETWEEN COLLOID STABILITY AND ZETA POTENTIAL

<u>STABILITY CHARACTERISTICS</u>	<u>AVERAGE Z.P.</u> <u>(Millivolts)</u>
Maximum agglomeration and precipitation	+ 3 to - Zero
Excellent agglomeration and precipitation	- 1 to - 4
Fair agglomeration and precipitation	- 5 to - 10
Threshold of agglomeration (aggregates of 2 to 10 colloids)	-11 to - 20
Plateau of Slight Stability (substantially no aggregates)	-21 to - 30
Moderate Stability (no aggregates)	-31 to - 40
Good Stability	-41 to - 50
Very Good Stability	-51 to - 60
Excellent Stability	-61 to - 80
Maximum Stability	-81 to -100 and beyond

Reference: (A.I.Ch.E., 1974)

6.0 LIME (CaO) AND LIMESTONE (CaCO_3) REACTION WITH SOILS

Although free lime (CaO) is relatively rare, the calcium ion (at ppm concentrations) is a very active species in nature. Calcium, mostly in the form of limestone (CaCO_3), is being constantly dissolved or precipitated where its complex solubility in saline solution so dictates. The role of CaCO_3 as a particle bridging or bonding agent is crucial in most consolidated or cohesive sedimentary materials.

Calcium carbonate is often observed in nature precipitating where relatively high calcium concentration "fresh" water meets relatively high carbonate containing seawater. In fact, this process occurs quickly enough that in many ocean fronting tropical countries calcium carbonate cemented sandstones can be mined annually as so called "beach rock".

The idea of deliberately mixing manmade lime with clay containing soils to provide a strengthening effect has been known for a long time. The Romans are known to have used a technique of mixing lime and reactive "pozzolanic" soils (so named for Puzzolan, Italy which has a volcanic soil which is highly reactive with lime). With this natural clay soil they were able to build very durable sub-bases for their roads, for which they have justly become famous. Even today, some of the techniques the Romans may have used are not completely understood.

The process of precipitation of CaCO_3 between mineral grains to act as bridging/bonding agents, widespread in nature, is apparently not used much by man. It is relatively slow, taking months, years or even centuries to completely fill all the voids in a sand or clay material. The results which nature achieves using CaCO_3 as a bonding agent can also usually be attained by using lime and reactive clays for bonding. Hence the process of carbonation (or sometimes carbonatation) is much more relevant to geologists than it is to civil or geotechnical engineers.

While it became clear during the course of this study that a greater predictability of the strength changes in soils which might result from carbonation processes would be desirable, it does not appear to have been extensively researched. Further research in this area would definitely be extremely useful in our studies of lime treatment of tailings materials.

The use of lime for strengthening soils during construction can be subdivided into two major areas: the science of lime stabilization and the art of "lime modification" of soils.

Lime stabilization and lime modification of soils are both practises which offer some insights into the factors which may be important in the action of lime (calcium) on soil. They are

(6.2)

reviewed here primarily in that context. These practises may also play a direct role in construction of embankments and containment structures in chemical tailings treatment.

In lime stabilization, there are usually specific objectives such as a minimum 1.75 mPa (250 psi) soil shear strength and test methods to determine field effectiveness.

Lime modification has been practised as an art or a trial and error process to achieve minor but essential changes in soil character. Such modifications tend to be made as "judgement calls" by field personnel without the benefit of scientifically proven tests or preparation procedures. Obviously, the process works, as this practise is growing and someday may even reach the level of "science".

6.1 Lime "Stabilization" of Soil

The use of lime for soil stabilization in modern times resumed with post WWII United States Army construction efforts. They began their first preliminary tests in 1946, but it was not until about 1955 that any significant non-army use of the technique had resulted.

Lime did not attain its current extensive utilization for stabilization until the mid 60's, probably because the durability of any lime stabilized soil material for road building purposes was critical to its widespread use. This needed to be proven by 5 to 10 or more years of use. However, since that time, the tonnage of lime used for soil stabilization has increased by several orders of magnitude.

6.2 Soil Stabilization Procedure

Table 6.1 indicates several of the major criteria which suggest that lime stabilization might be appropriate for a particular soil. The procedure for stabilizing soils with lime is typically the addition of dry lime at a rate of some 3 to 8% on a weight basis, as outlined in Table 6.2, to the upper 6 inches or so of soil to be stabilized. It is usually tilled into the soil with agricultural implements to assure uniform mix and wetted to provide ample moisture for the hydration reactions which occur. (Transportation Research Board, 1976).

The minimum objective of this technique is typically 1.75mPa (250 psi) shear strength, with a factor of 2 to 3 in safety above this required minimum often deliberately engineered into the design, to overcome field problems such as non-homogeneity of the soil at a particular site.

(6.3)

Although other soil additives have been tried for stabilization, such as portland cement or asphalt, for most soil conditions, lime (CaO) or slaked lime (Ca(OH)_2) lime stabilization methods have proven to be by far the cheapest and most effective way of improving the shear strength of clay containing soils.

6.3 Comparison of Oil Sand Tailings and Natural Materials

Based on the relatively low percentage of clay in average Oil Sands material, oil sands could be anticipated to be between sand and low-clay material, in Figure 6.1, and have a strength comparable to what would be expected of the appropriate percentages of sand and clay for natural soils. As apparent from Figure 6.1, the mere process of obtaining a "dry" sand-clay mixture, if it can be done, should provide some shear strength with no appreciable lime content.

The geotechnical properties of various soils, particularly the compressive strength of soil-lime mixtures, increase to a concentration of about 8% by weight of lime. Above this there is usually a much less significant increase, in some cases, none at all.

6.4 Effect of Curing Time

Figure 6.2 illustrates the effect of curing time of a 5% weight addition of lime for various sand, sandy clay, sandy gravel and silty clay soils. As is apparent, the effect is very gradual with time. With these particular materials there is no indication, after 84 days of cure, of any deceleration of the strength improvement effect. In fact, many researchers report that lime stabilized soils are still showing increases in shear strength after 10 years under field conditions.

6.5 Effect of Compaction Delay

Figure 6.3 illustrates that the process of lime stabilization is not greatly affected by the length of time after the lime is added and before the soil is compacted for the final time.

Some investigators have reported that lime stabilization is in fact enhanced if material as laid down is broken up, remixed and recompacted. The only concern with this procedure is normally that it may result in increased water consumption in the final soil mixture which, in a dry climate, may be difficult to satisfy.

6.6 Effect of Temperature

As illustrated in Figure 6.4, the rate of gain of shear strength of lime stabilized soils is inversely proportional to the absolute temperature at which the soil was cured. However, there is no indication that a more rapid curing caused by higher temperatures, has an effect on the ultimate strength unless extensive aeration takes place.

6.7 Effect of Soil Mineralogy

The relationship between soil composition and lime stabilization has been indicated to a certain extent in the previous discussions of the effect of lime on sand, sandy clay, sandy gravel, silty clay and other soil mixtures. However, it is known from the literature that the type of clay present in the soil has significant effects on the ultimate properties of lime stabilized soils.

Figure 6.5 illustrates the interrelationship of lime content, moisture content and several measures of the fluidity of the soil for kaolinite or montmorillonite clay minerals. Perhaps what is most significant for kaolinite is that the moisture content at the point where kaolinite clays begin to show fluid-like behaviour increases as a function of lime concentration. These so-called "liquid" and "plastic" limits show a break point at about 1% lime for kaolinite, although they continue to increase well beyond this point.

6.8 Mechanism of Lime Stabilization of Clays

Figure 6.6 schematically illustrates the principal mechanism by which lime, clay and water are believed to form new minerals which bond clay particles together.

As the figure illustrates, the lime solution, at high concentration is suspected of dissolving the edges of a clay plate the (silicate portion) and forming a gelatinous calcium silicate "glue" which is capable of slowly crystallizing the clay particles together. Some investigators believe the solubilization of silicates and aluminates requires a pH in excess of 11.5, at least locally around the particles.

A second mechanism, carbonation, as in nature, acts almost instantaneously (with excess CO_2) as CaCO_3 is formed by reaction with atmospheric CO_2 , providing "bridging" material between two mineral grains.

(6.5)

As the CaCO_3 bridging material is weaker than calcium silicate or calcium aluminate minerals which might be formed from pozzolanic reactions, attempts are usually made to obtain pozzolanic rather than carbonation reactions.

6.8.1 Pozzolanic Lime Soil Reactions

Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	Fast forming materials
Calcium Silicates	Ca_2SiO_4 $\text{Ca}_3\text{Si}_2\text{O}_7 \cdot 3\text{H}_2\text{O}$	
Calcium Aluminates	$\text{Ca}_3\text{Al}_2(\text{OH})_{12}$ $\text{Ca}_6\text{Al}_2(\text{OH})_{16} \cdot 12\text{H}_2\text{O}$ $\text{Ca}_6\text{Al}_2(\text{OH})_{16} \cdot 5\text{H}_2\text{O}$ $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	Slow forming

These crystalline species are responsible for the fixation of water in the crystals illustrated in Figure 6.6, thereby contributing to an increase in the solid content.

6.8.2 Carbonate Formation

If carbonate or bicarbonate ions are present, the formation of calcium and Ca/Mg carbonate precipitates can be expected, as the solubility of both is only a few ppm.

If there is relatively little carbonate or bicarbonate present but the pH is below the suggested threshold of 11.5 required for pozzolanic reactions, carbonate formation from atmospheric CO_2 will likely be the predominant mechanism of stabilization.² As CO_2 in the atmosphere is typically only 320 ppm and air infiltration in even a coarse, wet soil is relatively slow, the formation of calcium carbonate cement might be expected to take months or years. Also, due to seasonal effects, drainage patterns, temperature, air flow and a myriad of other factors the results of this type of stabilization reaction process are bound to be highly variable.

Obviously another limitation of this mechanism is that for most construction purposes it would be unwise to rely on carbonate

(6.6)

formation for any specific strength increase within a predetermined period of time.

6.8.3 Organics Interference

When organics such as humic acids or even bitumen are present, interference with the stabilization process may be expected. Organics can absorb on nuclei, thereby poisoning the growth of the crystals, or chelate the calcium. Chelation reactions can be overcome by extra calcium.

6.9 Hydraulic Lime Stabilization

As mentioned earlier, the process of lime stabilization is relatively tolerant of excessive moisture. In fact, it has been amply demonstrated now, after 10 to 15 years of experience, that lime stabilization can be used where a soil will later be under a static or flowing waterhead. The practise has become known as "hydraulic lime stabilization."

The literature on hydraulic lime stabilization has demonstrated that there is no need for concern about the possibility of the lime/clay stabilization system reversing itself when in long-term contact with water (Gutschick, 1978). "Hydraulic" lime stabilized soils are commonly used for canal bottoms and levees, tailings dams, and other embankments in permanent contact with water, with no fear that the process will reverse itself and the soil crumble or disintegrate.

This may be understandable on the assumption that hydraulic lime stabilization involves the formation of pozzolanic reaction products. If the lime treatment process resulted in carbonate formation it could be expected to have much greater susceptibility to water dissolution, particularly if the water were to be even slightly acidic, at which condition calcium carbonate solubility is substantially greater.

6.10 Lime Soil "Modification"

Traditionally lime stabilization is used to upgrade heavy clay soils to provide sub-base quality material for roads, runways or other civil structures. As mentioned the criterion is usually that a minimum compressive strength of 250 lbs/sq inch at 7 days cure time is required. However, there has been considerable experience with a so-called "lime modification" process which, in fact, uses less lime and requires less of a strength improvement in the soil

(6.7)

treated. It is typically used for improvement of access on wet sites or improvement of the workability and pulverization characteristics of clay soils.

While this subject has received less scientific attention it could be anticipated from information such as Figure 6.1 that the degree of strength change is proportional to the amount of lime used. At levels of a fraction of a percent lime, the strength change to be expected is slight, and may be less than the detection limits of typical soil measurement techniques.

There is very little scientific data at such low levels of lime addition, since the strengths in soil desired under the 250 psi level are subjective. Also, no standard test procedures are available to determine the characteristics of the treated material.

Tables 6.3 and 6.4 suggest situations in which lime soil modification might be tried and appropriate lime levels.

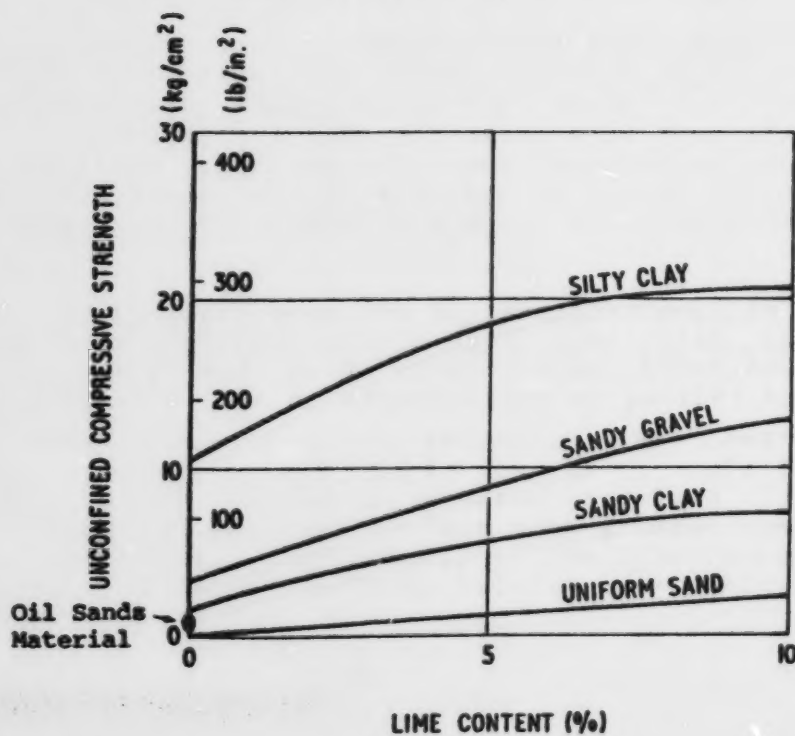
As may be seen, lime modification is not recommended for either sandy clays or high organic content materials such as would be expected for oil sands tailings, largely because reliability of the results is even more uncertain than is typical of other soil lime treatment techniques. Where the mechanism would be certain to be carbonation, it can be appreciated that the results are likely to be even more variable since atmospheric CO_2 is significant to the process.

The concept of lime treatment of oil sand tailings at low levels of clay and relatively high organic contents must therefore be carefully considered particularly from the point of view of producing and relying on improvements in soil strength properties.

(6.8)

Figure 6.1

Effect of Lime Content on Strength

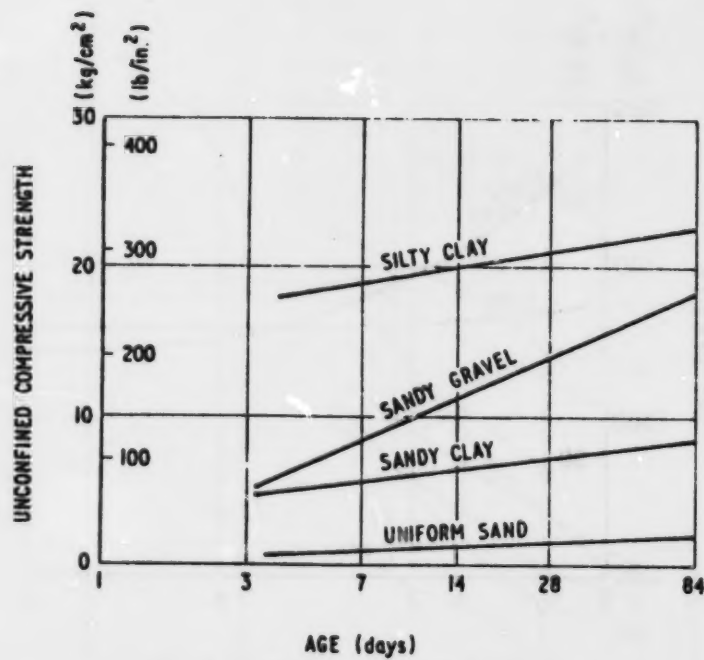


Ref: Ingles, 1973

(6.9)

Figure 6.2

Effect of Age on Strength

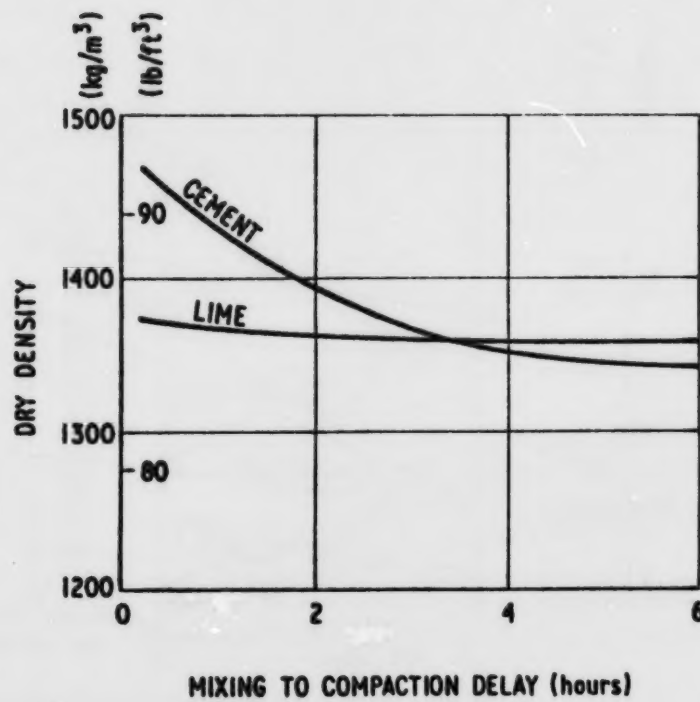


Ref: Ingles, 1973

(6.10)

Figure 6.3

Effect of Compaction Delay on Density

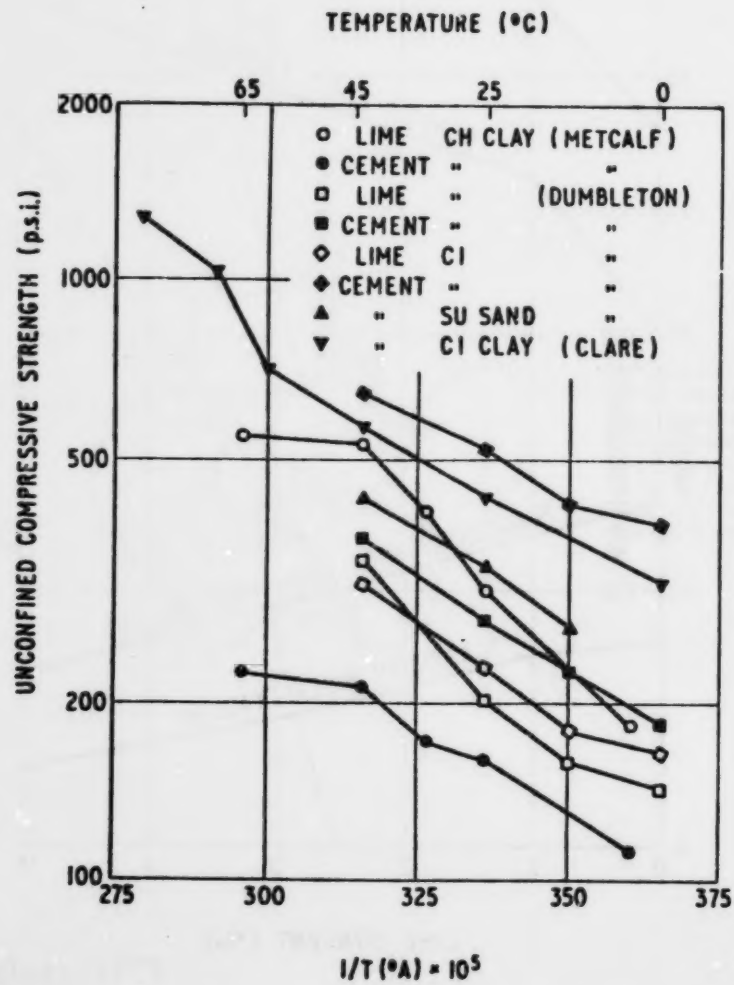


Ref: Ingles, 1973

(6.11)

Figure 6.4

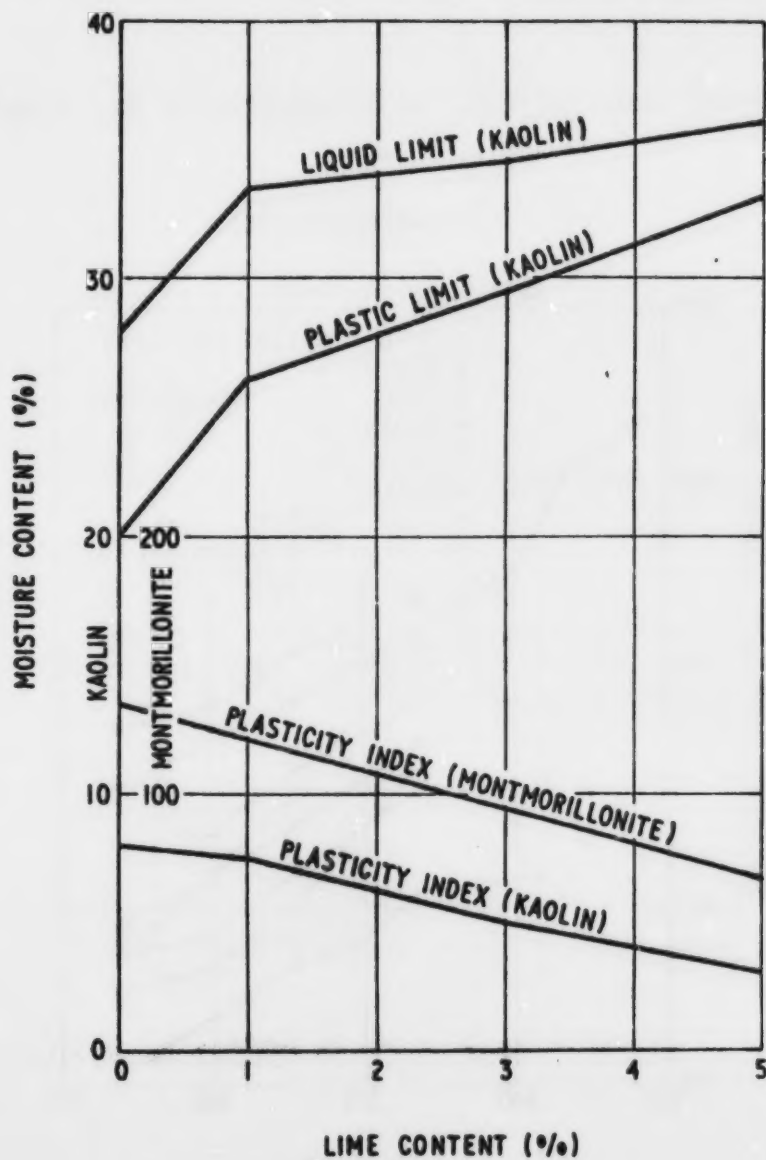
Effect of Temperature on Rate of Strength Gain



Ref: Ingles, 1973

Figure 6.5

Effect of Lime Content on Plasticity

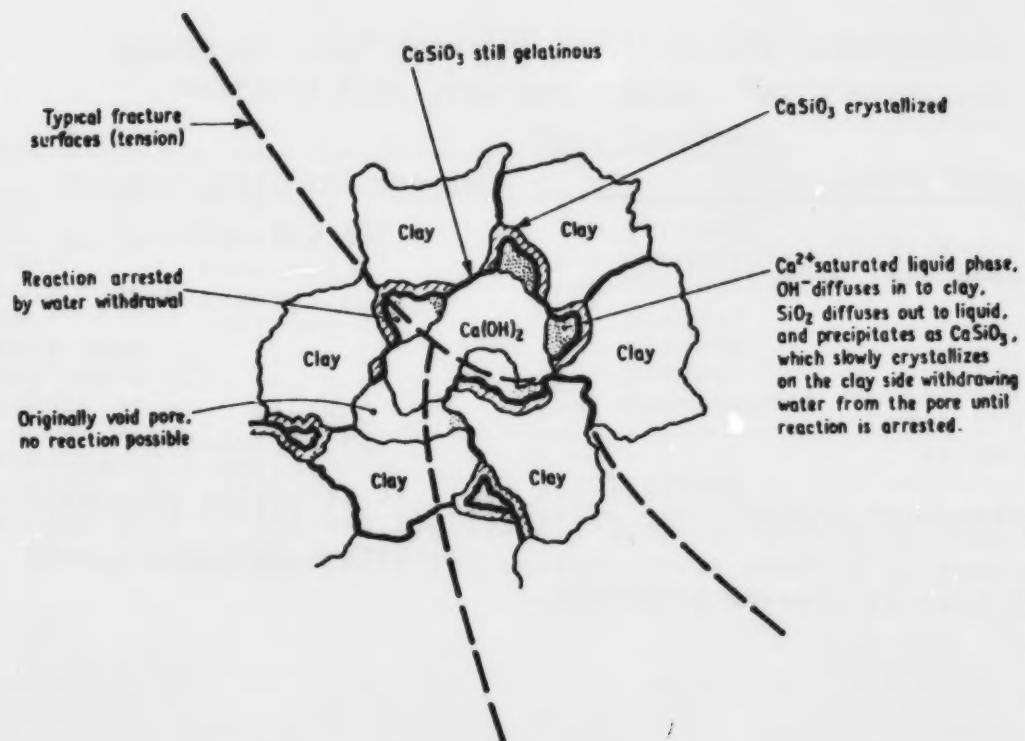


Note, however, that kaolinitic soils often show an increase in plasticity on lime treatment.

Ref: Ingles, 1973

Figure 6.6

Mechanism of Lime Stabilization of Clay Soils



Ref: Ingles, 1973

(6.14)

TABLE 6.1

SUGGESTED CRITERIA FOR SOIL LIME STABILIZATION

Process	Purpose	Requirement
Lime "stabilization"	Improvement of subgrade material.	Increase in bearing capacity
	Improvement of base	Decrease in swell
		Decrease in plasticity
		Decrease in swell Increase in strength or bearing capacity (min. CBR 80)

TABLE 6.2

SUGGESTED LIME* CONTENTS FOR SOIL STABILIZATION

Soil Type	Content for Stabilization
Fine crushed rock ⁺	not recommended
Well graded clay gravels	3 per cent
Sands ⁺⁺	not recommended
Sandy clay	5 per cent
Silty clay	2-4 per cent
Heavy clay	3-8 per cent
Very heavy clay	3-8 per cent
Organic soils	not recommended

* Hydrated lime Ca(OH)_2 as a percentage of dry weight of soil.

+ Lime only effective if fines are plastic.

++ Lime used in bitumen stabilization for promoting adhesion:
Quick Lime in loessal materials.

(6.15)

TABLE 6.3

SUGGESTED CRITERIA FOR LIME SOIL MODIFICATION

Purpose	Requirements
Improvement of access on wet site.	Large increase in plastic limit Rapid increase in bearing strength
Improvement of workability and pulverization.	Large and rapid decrease in plasticity. Increase in proportion passing 3/16 in. sieve.

TABLE 6.4

SUGGESTED LIME* CONTENTS FOR LIME SOIL MODIFICATION

Soil Type	Lime Treatment
Fine crushed rock ⁺	2-4 percent
Well graded clay gravels	1-3 percent
Sands ⁺⁺	not recommended
Sandy clay	not recommended
Silty clay	1-3 percent
Heavy clay	1-3 percent
Very heavy clay	1-3 percent
Organic soils	not recommended

* Hydrated lime $\text{Ca}(\text{OH})_2$

+ Lime only effective if fines are plastic.

++ Lime used in bitumen stabilization for promoting adhesion: Quick Lime in loessal materials.

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STUDY RESULTS

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7.0 TREATMENT OF "TOTAL" TAILINGS

The first effort to deal with the "total" oil sands tailings problem, or both sand and clay slurried tailings as produced by the hot water process, began at Syncrude in 1976, (Liu, 1980). With the realization that lime could be used to coagulate sand and clay and deposit both together, a process for treating and filtering oil sands tailings with inorganic water treatment chemicals was developed. This coagulation technique was tested as a pretreatment step for a filtration process on a 2.5 t.p.h. pilot scale.

The tailings filtration process has several major limitations for application on a commercial scale, not the least of which is that it would be expensive relative to current disposal technology. It also has practical limitations on filtration rates and wetness of cake for high fines materials, and with freezing of the wet filter cake material in the wintertime.

Syncrude's experience with the lime treatment sludge filtration process has suggested that it has relatively few problems in some of the main areas expected, such as recycle water handling, which is discussed more completely in Chapter 10. More particularly, it does not have a problem with excess calcium levels in the reclaim water interfering with extraction which was one of a number of fears about lime treatment which were apparently of concern to earlier researchers in this field.

This project team was aware of a considerable amount of work which has been done previously to optimize the chemical treatment of whole tailings for filtration (e.g. Fuhr, 1982).

The objectives in coagulation for direct disposal proved to be significantly different.

From a wide range of desirable characteristics and goals, we had first to select a number of process criteria and then prioritize these into a workable set of objectives.

7.1 Objectives

The initial program for the measurement of the coagulation and settling characteristics of whole tailings had the following objectives:

1. To obtain a homogeneous sand/clay settled mixture.
2. To obtain as rapid a settling rate as possible.

(7.2)

3. To obtain as low a water content in the settled material as possible.
4. To obtain the highest water quality possible for the decant water.
5. To obtain the above properties at the minimum chemical cost.
6. To obtain a settled material with the maximum permeability possible.
7. To produce the maximum possible shear strength material.

A number of these objectives are obviously opposites. For example, obtaining the best properties of the deposited material without consideration for the chemical cost would be expected to result in a more expensive system than one in which an attempt is made to minimize the chemical cost. We thus needed to prioritize several of these objectives and determine which of them could be routinely achieved (and therefore ignored). The difficult objectives could then become the central aims of the research.

7.1.1 Water Quality

From previous work with the lime treatment system, it was expected that the supernatant water quality would be far better than the minimum required for the oilsands extraction process recycle water. As water quality is normally the primary concern of coagulation and flocculation type water treatment methods for solids removal, standard coagulation and flocculation tests would not be particularly appropriate for our purposes.

7.1.2 Settling Rate

In addition to water quality, a secondary objective for most water treatment solids removal procedures is to maximize the settling rate of the solid material from the water phase. Because our material will be deposited hydraulically in a landfill, settling rate is also of relatively minor importance to us. It is significant only in the length of time elapsed before heavy equipment can rework the settled solids, if this is possible at all. While the current disposal operations use sand deposition from a pipe and dozer track-packing as a means of dyke construction, we soon realized that this method of construction would not be suitable, at least without first drying the material. The settling and drainage rates for treated whole tailings material would, of necessity, be slower than straight sand. From

the appearance of the material in the early flume tests (see the photo in Appendix B), immediate workability seemed out of the question.

7.1.3 Geotechnical Properties: Bulk Density and Permeability

For direct deposition of chemically treated material, the critical objectives thus became the geotechnical characteristics of the deposited material. In particular, the drainage rates (and therefore permeability) of the material and obtaining maximum density (and therefore shear strength) became our two main objectives, with permeability being perceived to be the most significant of the two.

Unless we could drain the deposited material in a reasonable period of time, the liquefaction hazard would remain high and the integrity of structures formed from the material produced by the treatment technology would be in doubt. However, if there was some way in which the material could be drained in a reasonable period of time to a condition under which heavy machinery could work on its surface, dyke construction by methods similar to those already in use would be feasible. The major concerns would then be only about the ultimate shear strength and liquefaction potential of the deposited material.

The secondary objective for the deposited whole tailings material was to produce from it a material that had a high bulk density. High bulk densities result in low liquefaction potentials and maximum integrity for soil structures constructed from a material.

7.1.4 Coagulation and Permeability Investigations

The geotechnical considerations are evaluated in more detail in Section 8 and Appendix B of this report; this chapter focuses on the coagulation and settling experimentation that was conducted to optimize the chemical dosage, using permeability of the settled material as the primary factor to be optimized.

The chemical treatment test program was basically conducted in two phases:

So called "Jar" testing, using a Phipps and Bird six place stirrer and a cone or "coffee" type filter apparatus, and column testing of coagulation, settling and permeability parameters simultaneously using a 3 metre plexiglas column. The apparatus and tests conducted are described in more detail in Appendix A of this report.

The tests with the Phipps and Bird stirrer and cone filter apparatus serve primarily as a prescreening tool to investigate the coagulation and settling properties of the material and the range of chemical dose rates required. The column serves as a "fine tuning" apparatus for adjusting the dose rates and the conditions used. It also allows measurement of compaction rates and permeabilities of the deposited sediments produced.

7.2 Coagulation, Settling and Permeability Investigations

The results of Zenon's work in identifying optimum dose rates for maximum permeability are discussed briefly here. (For more details on all of the items which follow, refer to Appendix A.)

7.2.1 Coagulant Dosage Rate

There are many factors which affect the dosage rates required to achieve coagulation of whole tailings. The major consumer of lime in the chemical treatment tests is typically precipitation of CaCO_3 due to high levels of bicarbonate present in the slurry water being treated. When the level of bicarbonate has been lowered to the equilibrium solubility of Ca^{++} and $\text{CO}_3^{=}$, the excess of Ca^{++} remaining in solution is free to react with other species such as the clays. Since both the levels of solids (45-55%) and the proportion of reactive clays (3-20+%) in the tailings solids is quite variable, the required dosage of calcium ion to produce optimal treatment of whole tailings can also be expected to vary proportionately.

For samples of commercial oil sands tailings taken during early to late 1983, the optimum lime dosage rate was determined to be in the range of 600-1000 mg/l, see Figure 7.1. (This dosage rate is based on the water phase of the tailings only which in these tests was adjusted to 65% by weight of the total tailings. It should be noted, that where used elsewhere in this report, ppm for dosage rates means weight on whole tailings, not just the water phase. The units mg/l refer always to concentrations in the water phase.)

7.2.2 Role of Polyelectrolyte

Previous work with lime coagulation of whole tailings suggested that lime coagulation would result in bulky, slow settling flocs. This can be overcome to a significant extent by using a "coagulant aid" (as discussed in section 5.0). Coagulant aids can increase the density and the permeability of settled solids simultaneously due probably to the unique orientation of flocculated particles

they can provide.

The optimum dosage for coagulant aid, (in combination with lime) for the chemical treatment step was determined to be around 8-10 mg/l (at an optimum lime dosage of 800 - 900 mg/l), see Figure 7.2.

7.2.3 Other Factors Affecting Chemical Dosage Rates

Among other factors which influence the coagulation process, a normal tendency to self-coagulation and significant influence of pH on chemical effectiveness can be expected. Both were investigated for samples obtained and found to be of minor significance: no self flocculation was observed, and normal pH related behaviour verified.

7.2.3.1 pH Factor in Coagulation

The pH dependent coagulation occurring with oil sand tailings material is also of interest in these tests as the high pH at which the material flocculated with NaOH (10.5) was very close to the optimal results and pH (10.55) with CaO (800 mg/l). Hence, it may be that the main result of the lime addition is a pH dependent charge reduction.

7.2.3.2 Other Inorganic Coagulants

The possibility that lime would work better in conjunction with other inorganic water treatment chemicals, (which happens occasionally in conventional water treatment) was investigated and found to be not the case for oil sand tailings.

7.3 Effect of Mixing Conditions on Settling Rate and Permeability

Figure 7.3 illustrates the effect of different "rapid-mix" periods in the range of 2 to 30 minutes on the settling rates (and ultimate settled density) of whole tailings material. As can be seen in the figure, there is no dramatic change in the settling rate (or the settled density) with longer mix times. However, both the ultimate settled density and the turbidity of the supernatant decant water were gradually improved with the longer mix times.

Thirty minutes was chosen for further settling test work as the

optimum rapid mix time, as the results were marginally better. If it were not possible to obtain such a long residence time in the normal pipeline transportation period in a commercial environment, shorter mix times could obviously be used without fear of significantly different results.

In all cases, 30 second residence time was used for the polymer addition as it does not need the long contact period, and may tend to be degraded to some extent by exposure to agitator action.

7.4 Major Test Results for Chemical Treatment Conditions

The following points summarize the major findings of the treatment test program (see Appendix A for further details):

- 1) The combination of about 800 - 900 mg/l lime plus 8 - 10 mg/l polymer gives the fastest settling rates (after additional tests on other batches of samples). Typical performance is indicated in Figure 7.4.
- 2) Lime plus polymer also give the highest settled density (lowest % H₂O on settled material).
- 3) Lime plus polymer give the fastest dewatering solids (two other treatments were comparable for this parameter).
- 4) The lime plus polymer tests give the lowest total solids in supernatant (within the test accuracy; two other tests were comparable).
- 5) Lime plus polymer significantly reduces supernatant T.O.C., though acidification is more effective.
- 6) Lime plus polymer gives the lowest moisture content of solids after both settling and filtration.
- 7) There is no significant difference between the two coagulant aid polymers tested. (A-110 has since been used for all subsequent tests as it is about 70% of the cost of A-137.)

7.5 Supernatant Water Quality From Coagulation and Settling

Table 7.1 is a summary of water quality parameter measurements for supernatants from several different coagulation experiments. Of interest is the fact that in all cases the level of turbidity or suspended solids in the samples is far below the desired goals for extraction water recycle. In fact, it is believed that all parameters related to water recycle quality are well within the

known requirements for extraction water recycle. (Water quality is discussed in more detail in Section 10.)

One parameter of even minor potential concern is silica, which in some experiments builds to levels in the range of 150 to 200 mg/l and which could possibly cause fouling problems if the pH of the water downstream is adjusted downwards, (the opposite of what is normally expected). In a system in which there is no sand or other nuclei present to prevent settling on boiler or heat exchanger tubes or vessels, also unlikely, it could present a problem.

All other parameters are well below the minimum levels at which there would be concerns for recycle water in these tests. By continued recycle over a period of years, chloride or other constituents of the process water could build up to a level which might be potentially harmful to the process. This is a subject that is also investigated in more detail in Section 10.0.

7.6 Settled Material "Compressibility"

Pressurizing the settling column caused the anomalous result of increasing the settled material density. The effect is particularly pronounced at the maximum applied pressure differential approximately of 100 K Pa (15 psi). The reduced volume of the solids portion of the column indicates the presence of "compressible" material. Since the solids are clays and sand grains which are known to be incompressible, either particle orientations somehow change due to the pressure or the material must contain some extraneous substance which is compressible.

In fact, as became evident in other tests, even when deliberate attempts are made to minimize the amount of air entrainment which oil sands tailings materials experience with even minor agitation, significant amounts of air are apparently still entrained in the samples. This apparently causes the compressibility evidenced in this experiment. Where it occurs, it is also likely to be a pronounced source of the clay-sand segregation that has been witnessed in some tests. This apparent tendency for the samples to segregate when air is present seems to be due to the ability of air to attach to the finer oil-coated clays and float them upwards.

7.7 Scale-Up Considerations

The possibility of air entrainment is one of the factors which must be taken into consideration in any design for commercial application which might otherwise involve open tanks or material that is known to contain air from air flotation in the extraction plant. For this reason chemical addition and mixing on a

(7.8)

commercial basis should probably be accomplished with in-line mixers and chemical injection systems which specifically exclude any air from the tailings. (Static or dynamic in line mixers are commercially available.)

To provide the required mixing at least cost, some larger scale (ideally, a 24" line) experimentation would ultimately be useful. For example, can a static mixer provide proper distribution of lime into the slurry? Assuming a separate mixer for polymer because of the wide difference in residence times, could a static mixer provide sufficient mixing for the polymer?

Obviously, a lot of such questions will require pilot and perhaps commercial testing of continuous flow equipment and methods.

Some of these considerations are discussed in Section 15.0.

Figure 7.1

Effect of Lime Dosage on Settling

Lime dose:
mg/L as CaO

□ 500
x 600
o 700
Δ 800
· 900
* 1000

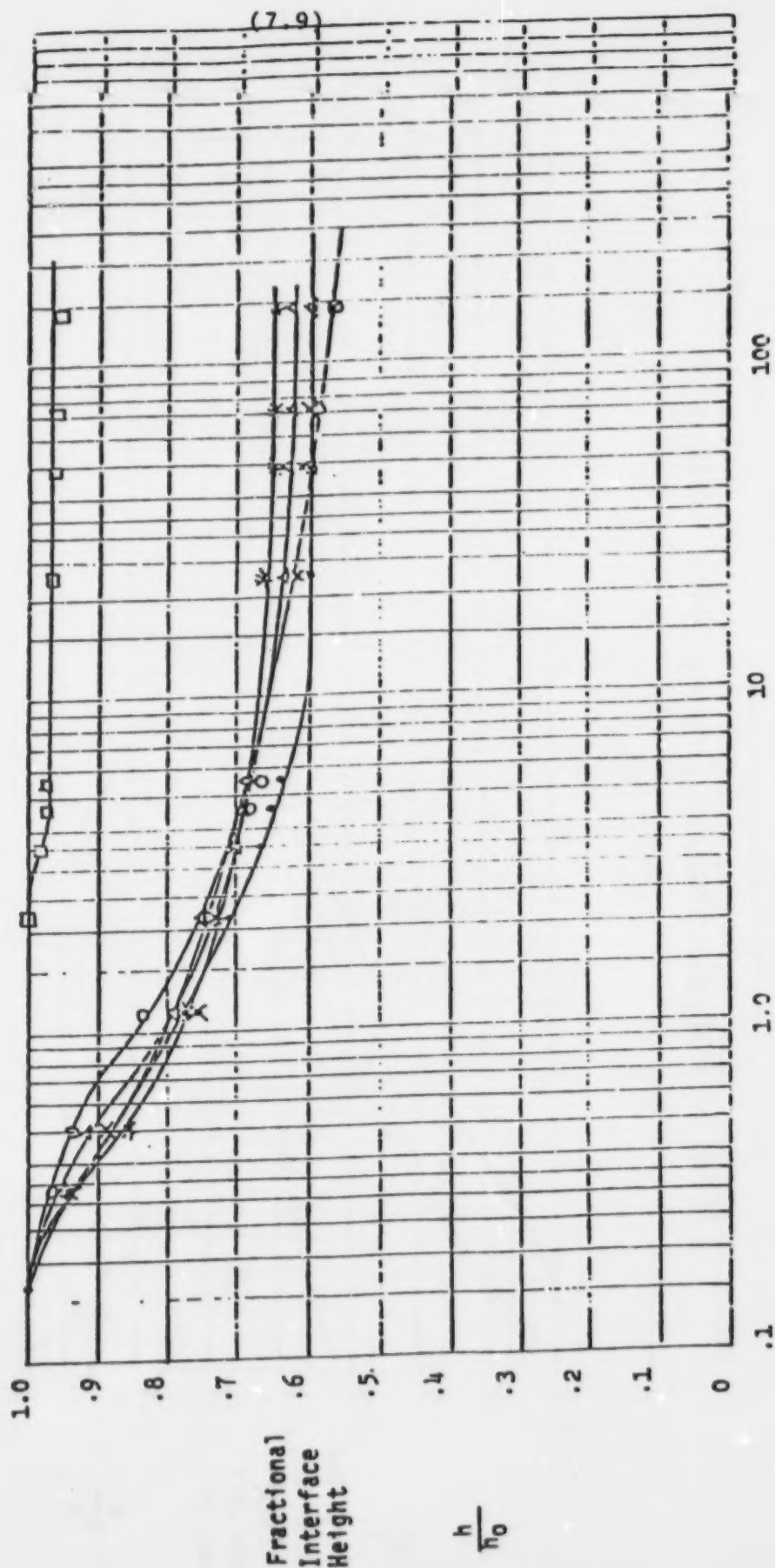


Figure 7.2

Effect of Polyelectrolyte Dosage on Settling

Lime Dose:
 900 mg/L as CaO
 A-110 dose - mg/L
 • 0
 x 1.0
 o 2.0
 + 3.0
 Δ 10.0

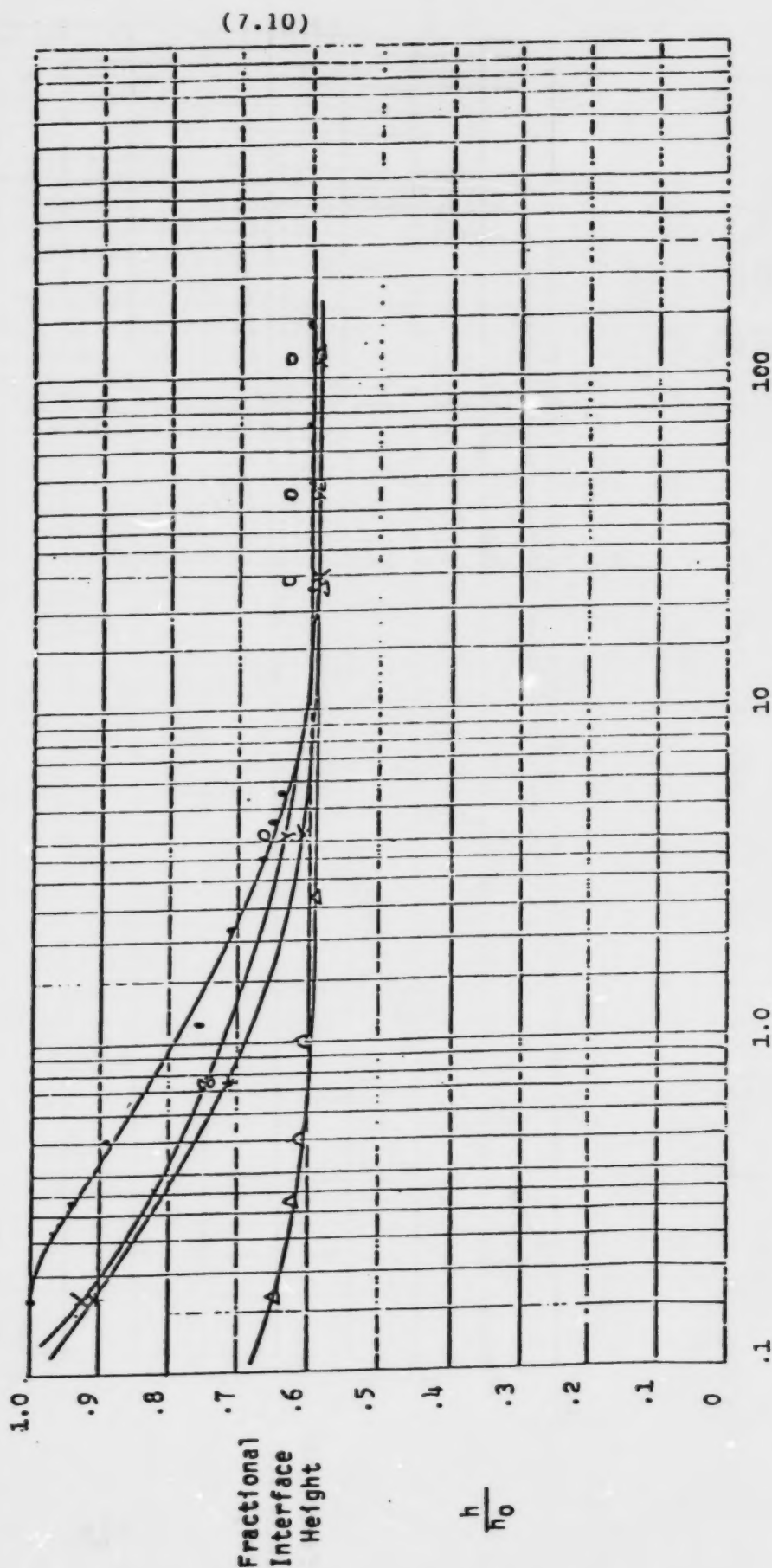


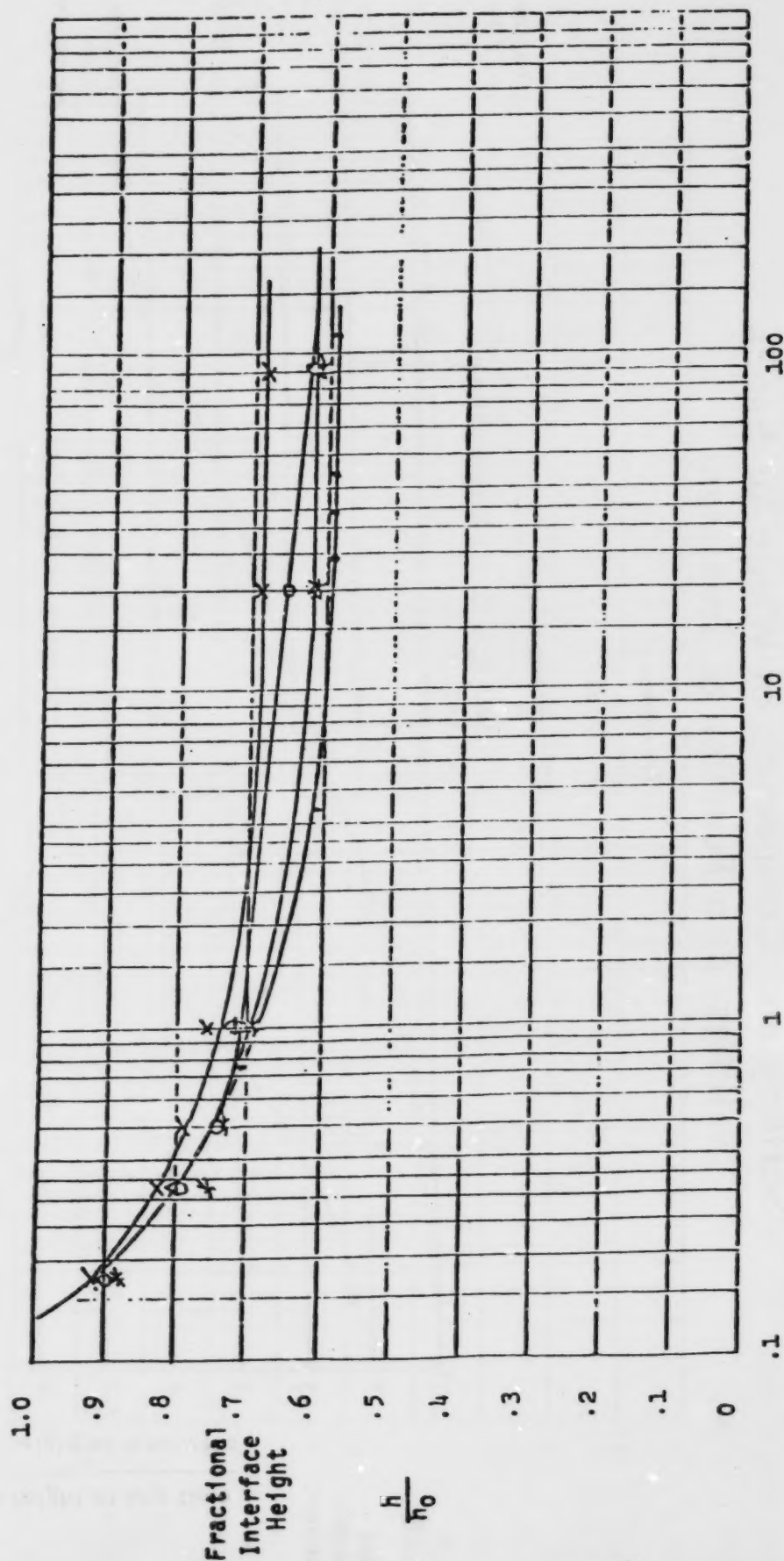
Figure 7.3

Effect of the Length of Rapid Mix Period on Settling

Lime Dose:
900 mg/L as CaO
A-110 dose 3 mg/L

Rapid mix period - min.

x 2
o 5
Δ 10
* 20
· 30



ELAPSED TIME - HR.

Figure 7.4
Settling and Compaction of Whole Tar Sands
Tailings, as a Function of Treatment

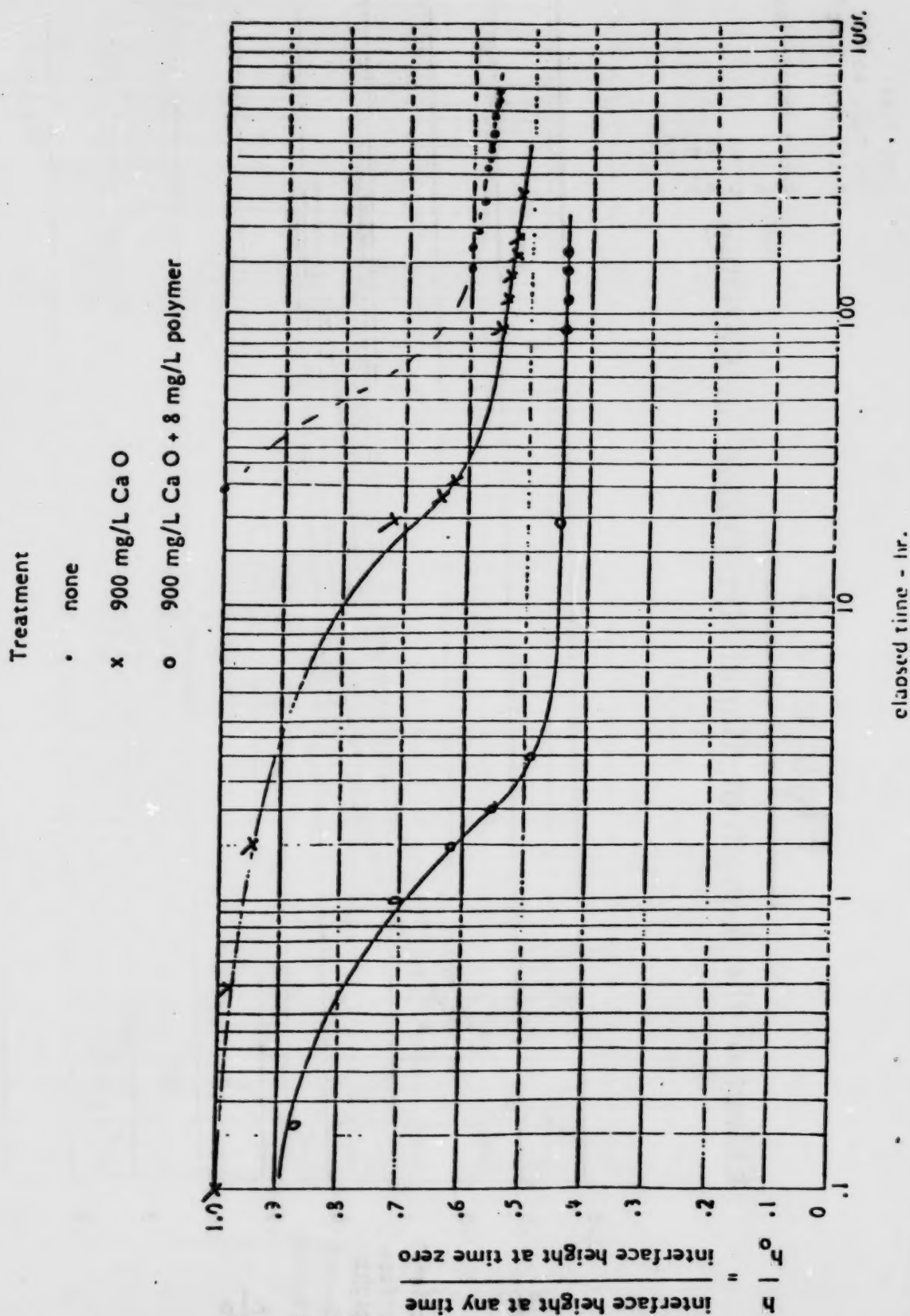
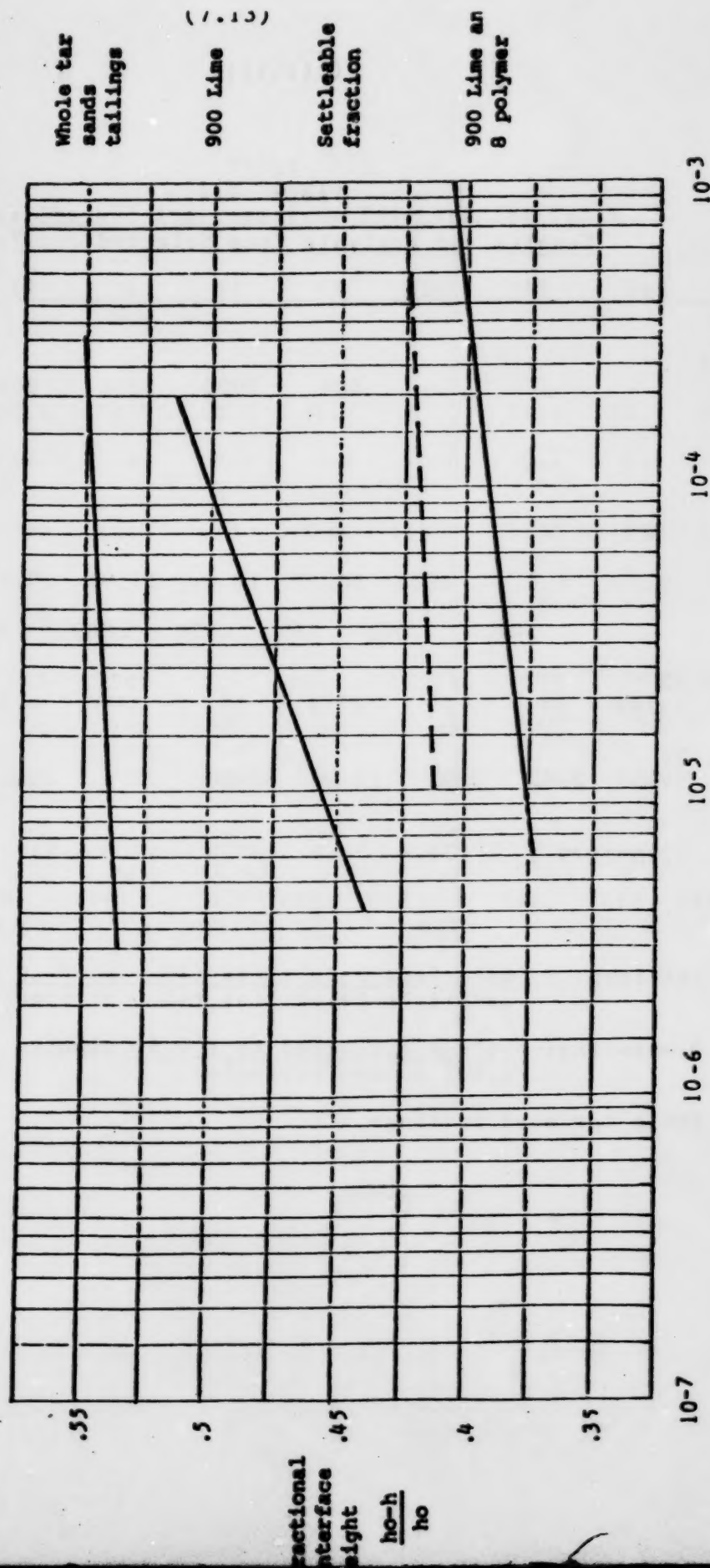


Figure 7.5

Comparison of Sediment Permeability as a Function of Compaction and Treatment



(7.14)

TABLE 7.1

Results and Analysis from Selected Jar Tests

Run	Raw	1	6	9	11	12	13	14	15	16
Parameters										
Lime Dosage mg/l	-	-	-	800	2000	3000	800	800	800	800
FeCl ₃ dose mg/l	-	-	-	-	-	-	400	800	-	-
A-110 dose mg/l	-	-	-	-	-	-	-	-	6 (A-137)	6
pH	7.7	4.6	10.5	10.55	10.6	11.95	9.1	7.7	11.3	11.1
Settling*	-	.397	.071	.550	.938	.882	.500	.600	1.0	1.0
Supernatant SS mg/l	33283	30	27	22.5	30	37	9.5	14.0	19.5	37
Supernatant TS mg/l	34357	2192	3691	1379	5392	7270	1360	5392	1384	1382
Sludge %wt H ₂ O	72.6***	79.1	72.9	76.1	53.8	42.6	44.8	44.0	34.2	36.7
Dewatering**	.333	.542	.160	.339	1.0	.971	.410	1.0	1.0	1.0

* Settling: $\frac{\text{interface height (at t=0 - at t=60 min)}}{\text{interface height (at t=0 - at final time)}}$

** Dewatering: $\frac{\text{volume collected at t = 60 minutes}}{\text{total volume collected}}$

*** Whole tar sand tailings

(7.15)

TABLE 7.2

Results and Analyses from Selected Jar Tests

Run	Raw	1	6	9	11	12	13	14	15	16
<u>Parameters</u>										
Dewatered % wt H ₂ O	83.0	70.5	70.9	52.6	31.7	37.9	32.1	33.3	29.7	28.5
Supernatant Quality										
Turbidity NTU	83	5.4	64	6.8	1.6	0.9	6.9	8.8	14	
Conductivity u mho/cm	2610	3730	5440	2610	8500	11550	2720	4080	3380	
Total Hardness mg/l CaCO ₃	32	192	<2	<2	868	1300	24	372	20	
Alkalinity mg/l CaCO ₃	589	0	2309	513	1824	2561	107	108	576	
TOC mg/l	174	19	130	58	34	31	46	72	37	
SiO ₂ mg/l	22	104	42	104	27	13	24	23	98	
Ca ⁺⁺ mg/l	6	43	3	3	262	442	9	90	8	
Al ⁺⁺⁺ mg/l	140	2.9	47	3.8	0.6	0.3	0.2	0.3	2.8	
Fe ⁺⁺⁺ mg/l	12.1	47.4	1.3	0.2	0.1	0.1	0.2	0.1	0.2	

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8.0 DISPOSAL SYSTEM SIMULATION TESTS

This section overviews work to identify the optimal geotechnical (soil) characteristics of whole oil sands tailings as they relate to disposal system design. A detailed discussion of experimental apparatus and procedure is presented in Appendix B.

8.1 Scope and Objectives

As discussed in section 7.0, the investigation was able to focus quickly on the two geotechnical properties of major concern for disposal design purposes: deposited solids density and permeability.

8.1.1 Dry Bulk Density

The dry bulk density of a soil material is a major factor affecting the geotechnical stability of an embankment. The higher the bulk density, the lower the potential that a particular material might tend to slump or fail, all other factors being equal. For minerals such as mixtures of silica sand and clay, (both of which have specific gravities of 2.65) a dry bulk density of 2.65g/cc, (165 lb per ft³) is never obtained in practice. Typical natural soils ideal for vegetative growth contain "void" space, occupied by air or water, which reduces the "dry" bulk density to perhaps 1.5 (95 lb/ft³). Such rich, high clay containing natural soils, may be too low in density to have satisfactory stability for construction of water retaining embankments.

8.1.2 Shape and Sorting of Particles

The "shape" of mineral particles and the degree of "sorting" are significant factors influencing the attainable maximum bulk density of soil particles. If the particles are, for example closely sized rounded sand grains, they are physically capable of closely "stacking" at bulk densities of up to 1.75. The density could be even higher if the particles are "well sorted" in widely varying sizes.

Sedimentary sand or silt grains deposited from flowing water (as is common in oil sands) can have fairly closely sized and also nearly spherical particles, due to the abrasion of the particles against each other. Where the particles are non spherical and angular, the attainable bulk densities would be significantly

(8.2)

lower, approaching those of natural soils, mentioned earlier, or even lower.

If such a material is piled too steeply at too low a bulk density, it could be unstable when wet, resulting in a slope failure.

8.1.3 Moisture Content and Permeability

An embankment is less stable when wet, due largely to the ability of water to act as a lubricant for relative motion between mineral grains. Also, the fact that water is incompressible and able to flow through soil materials ensures that the stress due to a hydraulic head of the water, will be transmitted throughout the embankment and find any local weak area within the structure.

The ease with which water can cause otherwise stable dry soil embankments to fail is a major reason why it is wise to conduct a close analysis of water saturation, permeability and hydraulic heads in soil embankments in which the bulk density may be lower than the liquefaction "steady-state density".

A homogeneous material, settled from a flowing slurry, would, almost certainly deposit at a natural angle of repose that is stable when resaturated with water, with no external loading. However, when subsequently loaded, (e.g. due to burial) it is possible that less stable types of material, such as a high clay content soils could fail catastrophically.

One of the objectives of geotechnical investigations is to determine whether there is any potential for this to occur.

8.2 Treated Tailings Disposal Simulation

8.2.1 Flume Testing

Field disposal of whole tailings primarily envisions deposition by discharge from a pipe, or overboarding as is currently practised. In order to evaluate how the chemically treated whole tailings might behave under these conditions, a small scale discharge test method is required. Figure ES.1 is a photograph of a plexiglas "flume" constructed to allow pouring of +20 litre quantities of treated whole tailings for subsequent drainage, drying and geotechnical evaluation.

8.2.2 Permeability Measurements

Three separate pieces of apparatus were used to measure the rate of movement of water through deposited tailings material vertically and horizontally under various conditions of hydraulic head. The pieces of apparatus used included a constant head permeameter, a 3 metre column permeameter to study segregation and consolidation behaviour and a smaller "dyked" flume apparatus to evaluate horizontal permeabilities.

The apparatus and procedures used for all tests and results obtained are described in detail in Appendix B.

8.3 Geotechnical Tests

From the previous discussion, it can be appreciated that the primary concern of depositional simulation testing is to determine the densities and permeabilities that can be obtained. Other relevant properties are "unconfined compression strength" (UCS) which is an indication of the load bearing capacity of the material, and the densities and shear strength the material attains due to compaction.

The tests conducted and the results obtained are discussed in detail in Appendix B.

Application of the geotechnical data to the design of conceptual disposal systems which take full advantage of the unique properties of chemically treated whole oil sands tailings is discussed in section 11.0.

8.3.1 Flume Tank Testing

Fairly early in the flume test experiments conducted by Terracon there were problems in obtaining results comparable to those at Zenon's optimum chemical dosage levels. In these early experiments by Terracon, the 900 mg/l lime and 8 mg/l polymer dosage levels (on liquid only, or perhaps 500 ppm lime, 5 ppm polymer on both water and solids) showed a tendency to segregation of the fine and coarse material in the flume. It also washed out a significant amount of the fines in the runoff water. By this point in the experiments, there had been no indication that the type of mixing arrangement being used was causing significant air entrainment in the material, or that this air entrainment was largely responsible for the segregation (flotation) of fines.

The cause of this problem could not be determined in the early experiments, but by trial and error it was later determined that a higher lime dosage level, namely 1,500 ppm on whole tailings, was capable of overcoming the tendencies to segregation and fines washout that were evidenced in the earlier experiments. It was

also found that 900 ppm lime and 8 ppm polymer by weight on total tailings achieved this same objective of preventing segregation and fines washout.

While it was subsequently found that the elimination of entrained air allowed operation at lower chemical dosages, (comparable to Zenon's levels) most of the experiments in the flume test programs had already been completed at the higher dosages. Obviously, confirmation of the workability of the lower dosages is desirable.. (Zenon's dosages can typically be converted into ppm weight of chemical to total weight of tailings by assuming 45% water, as was found in the early samples they tested. Subsequent samples were adjusted to this same level with distilled water.)

"Clear" water begins to break out almost immediately upon deposition of the material in the flume. The runoff water from the experiment is collected in a container at the discharge end of the flume and the runoff is allowed to continue with gravity as the only driving force for water discharging from the material deposited.

In some of the experiments conducted, two or more batches of whole tailings were prepared and discharged into the flume, so that one batch of material would be underneath the final batch deposited, to provide a contact and drainage surface more representative of field conditions. The initial material deposited in the flume would usually be allowed to drain for several days before a second batch of material would be placed upon it in the flume. No tendency of the first layer to liquefy was noticed upon discharge of additional slurry on its surface.

While free drainage of moisture from the sample stops within about two days after initial deposition, further reduction in moisture content occurs by air-drying under the ambient conditions in the laboratory. Because the maximum depth of material in the flume is only about a foot, and the resistance to flow through the material is relatively high for this small depth, there is no further flow, due to the hydraulic head in the flume apparatus. Further loss of moisture from the material is expected to be limited by permeability and capillary moisture retention effects which have been tested and evaluated in separate tests discussed in Sections 8.4 and 8.5 of this report.

It is recognized that air-drying is a function of temperature and humidity and that the conditions experienced in the lab are not likely to be representative of field conditions.

In the laboratory experiments, the material required approximately one to three weeks of drainage and/or drying before it achieved a consistency which would be trafficable for heavy equipment. Such equipment would be needed in the field for compaction and for soil movement for dyke construction purposes.

Obviously these assumptions and the actual rate of drainage and drying which would be experienced under field conditions must be measured in a representative environment for a proper estimate of the optimum design parameters and conditions.

The flume experiments do suggest that if allowance for a time delay for drainage is provided, the treated tailings will be amenable to a disposal system design in which the material is used for construction of embankments for self-impoundment.

8.3.2 Grain Size Analyses

It is of particular interest that fine silts and clays normally present in the tailings seem to "disappear" after the chemical treatment. In fact, the fines seem to be coagulated or bonded with coarser materials in such a way that their individual grain size characteristics are no longer evident. Materials with such an apparent lack of fines would, of course, be expected to show properties such as density and permeability more like sand than clay. However, as will be appreciated from subsequent tests such as "capillary moisture retention" discussed in section 8.5, the clays are still present but effectively "tied up."

8.4 Permeability Measurements

The rate of movement of moisture through the deposited soil is probably the most critical parameter for the design of a tailings impoundment system. The rate and extent of movement of water in a soil sample is governed by both the permeability of the soil to water and its "capillary moisture retention". Permeability and capillary moisture retention can be and has been measured by several types of equipment including "constant head" rate apparatus, a vertical column permeameter a "dyked" flume and a "capillary head" apparatus. These different pieces of equipment and the experimental procedures used to determine soil permeabilities are discussed in more detail in Appendix B of this report.

The following observations regarding these tests are noted:

After 159 hours i.e. one week approximately, the three metre column of sediment had reached drainage equilibrium. In effect, whole tailings sand layers with only vertical drainage (no lateral drainage) would be effectively drained in approximately one week.

Permeability measurements for the whole sand/clay mixture are intermediate between sand in the range of 10^{-3} to 10^{-4} and sludge in the range of 10^{-8} to 10^{-9} . The permeability of the material (at about 10^{-4} cm/sec in several cases) approaches that of dyke sand. This permeability is also directly comparable to that in the beaches of Syncrude or Suncor's dykes and as such is

definitely be considered as usable as building material.

Current construction methods, as discussed in section 4.0, involve overboarding material on these beaches. It should be noted that conventional hydraulic construction methods result in a product which has approximately four times higher horizontal than vertical permeability, on average. The normal dyke and beach variations in permeability, along with gradations in permeability, due to the settling process which occurs during dyke construction, result in very significant vertical inhomogeneities in permeability.

While the current situation has obviously been workable, it would definitely be very advantageous from an engineering viewpoint to produce a material with less variation in permeability and more equal horizontal and vertical permeability. Horizontal permeabilities for treated whole tailings are comparable to the vertical permeabilities of this material.

Material produced in the flume test has not and can not experience any significant individual grain compression. Material which would be buried under a significant height of subsequently discharged material at field conditions would be subjected to considerable self-weight consolidation, thereby significantly reducing its permeability. Permeabilities should therefore be measured over a significant range of compactive forces to determine the relationship between imposed pressure and void ratio.

While the data produced by Zenon show a limited extent of imposed pressure it would be valuable to determine permeabilities at higher applied pressures. It would also be valuable to develop a computer model of the movement of moisture within structures constructed of treated tailings.

Permeability values are those reached at equilibrium. The considerable time required to reach equilibrium is probably a result of soil structure changes which are taking place within the whole oil sands tailings as a result of the movement of the fines.

8.5 Capillary Moisture Retention Measurements

Early in the course of the flume deposition experiments it became apparent that the material was retaining moisture for a longer period than would be anticipated for a sand-like dyke building material, or material with the apparent grain sizes exhibited in the sizing tests. In order to confirm whether or not the material had moisture retention properties that would be anything other than what would occur with the fine-grained clays present, a capillary moisture retention apparatus was constructed.

The material exhibits a capillary hydraulic head equivalent to approximately 1 metre. The significance of such a hydraulic head

(8.7)

is that the moisture in the material will be retained at a height of approximately 1 metre above the surrounding water table due to the capillary action of the fine clay particles drawing water from below. This "capillary moisture" appears to be consistent with the known grain sizes of the clays present.

In a commercial disposal operation, this means that the water table for disposed material would have to be drawn down at least 1 metre before the surface of the material would begin to dry. Although this observation should be confirmed under field conditions, its significance is that by monitoring the water table of the deposited material with piezometers, we should have a safe means of determining when the material is capable of supporting heavy equipment. It should also be noted that, although this moisture is a potential geotechnical problem, it may be very beneficial for revegetation.



9.0 CURING AND STABILIZATION TESTS

When whole tailings, treated with lime or lime and polymer, is settled in a beaker and allowed to dry in an oven it cures in several days to a solid "cinder-block". It can be dumped from the beaker as a solid cylinder in the shape of the container. Although the cylinder seems quite rigid and looks and feels like a sugar-cube (it seems to have a relatively high shear strength), when brushed lightly with a finger the surface disintegrates to individual sand grains.

While the above example is certainly not representative of commercial disposal conditions, it does suggest the question: "How much (if any) of the apparent bonding is due to the action of the chemicals?"

A variety of curing, shear strength testing and mineralogical investigations have been conducted in an effort to answer this question.

9.1 Mineralogical Investigations

Three general methods of investigation were used for evaluating the mineralogical impact of the chemical treatment: X-Ray Diffraction, Thermal Gravimetric Analyses and Differential Thermal Analysis. These techniques were intended to identify any new minerals such as calcium silicate, calcium aluminate or calcium carbonate formed by the treatment process.

Thermal Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) are very sensitive calorimetric tests to identify, if present, stabilization reaction products. These tests were done for us at the Waste Water Technology Center of Environment Canada in Burlington, Ontario. We are grateful for the assistance they have provided on this work.

9.2 Unconfined Shear Strength (UCS)

One of the most important geotechnical characteristics resulting from the chemical treatment is the extent to which treatment increases the load bearing capacity, or shear strength of the tailings material. Shear Strengths of materials can be determined by "Unconfined Shear Strength" testing using a "triaxial" test apparatus. Related test procedures and results are described in Appendices A and B.

Trying to simulate field conditions under which tailings would drain and dry, proved to be a challenge, primarily because field conditions would be inherently variable in temperature, moisture content and other major factors. Also, from the literature, dry stabilization processes occurring at low chemical concentrations might be expected to take perhaps months or years. In order to obtain meaningful results within a reasonable time period, it was decided to use extremes of moisture content (from dry to completely saturated) and work at room temperature and higher. (The literature suggests that higher temperatures will influence the rate of stabilization processes, but probably not the ultimate strength developed). Also, rather than test a variety of different chemical dosage rates, it was decided to use the preferred chemical dosage for lime plus polymer and a high level of lime for testing. The rationale for the high level of lime dosage was that if the resulting effect (expected to be a small one) was not apparent at a high dosage of lime, it would be even more difficult to detect at a lower dosage rate.

Unconfined compression strengths were also determined for some of the samples taken from the flume tests as a function of "curing" time. Procedures for these tests and results are discussed in more detail in Appendix B.

9.3 Results and Discussion

9.3.1 Calorimetric Analysis

The T.G.A. scans show little evidence of reactivity, except for some unidentified endotherms for the lime treated system, an example of which is provided as Figure 9.1. (These also show up on D.T.A. scans.)

The D.T.A. scan for lime plus polymer treated material also showed an endotherm at 860°C which could be CaCO_3 dissolution (which normally occurs at 825°C).

For treatments with 1500 mg/l, and even 10% lime the results of these tests are not inconsistent with the formation of a small amount of some new mineral species, near the detection limits of the apparatus. However, the apparent levels indicated are so low they are almost outside the detection limits of the apparatus.

The results are consistent with what would be expected of a carbonation stabilization mechanism.

9.3.2 X-Ray Diffraction

Samples were submitted to the Ontario Research Foundation for mineralogical analysis by X-Ray diffraction. X-Ray diffraction revealed the probable presence of trace amounts of carbonate minerals, as well as a trace amount of an unidentified species.

The results are also consistent with a carbonation type soil stabilization mechanism.

9.3.3 Unconfined Compression Strengths

Table 9.1 is a synopsis of the results of the UCS investigation. Table 9.2 provides a basis for comparison with common soil materials.

At first glance, the results are both puzzling and somewhat surprising in that significant strengths developed in many of the samples. Relative to Table 9.2, it is evident that several of the samples can be considered as either extremely weak or very weak rock at a UCS of 8 to 12.5 kg/cm².

It is recognized that UCS testing typically gives results with an inherently high degree of variability. Hence, any conclusions drawn from the data have uncertain statistical validity without multiple replicates for individual test conditions. (Multiple replicates were not feasible within project time and budget constraints.)

With this limitation in mind, the following deductions from the results are offered more as hypotheses than as conclusions:

- 1) Samples which remain fully saturated show lower strength development than samples in air, at any condition.
- 2) Excluding the 190 day and high lime dosage conditions, there appears to be a gradual strength development with time in all of the other samples.
- 3) There is little, if any, temperature dependence evident in the results.
- 4) There appears to be no significant difference between dry air and humid air in the strengths developed for any particular elapsed time (including the 190 day samples).
- 5) Assuming that some segregation of samples occurred during the settling process used to prepare the samples, it is believed that observations 1-4 above are consistent with an air derived CO₂ carbonation process. Such a mechanism is not affected by air or sample moisture content, but is affected by the amount

(9.4)

of air which has come in direct contact with the sample. Since the saturated (submerged) samples had much less exposure to air, strength development is significantly impeded by the greatly limited absorption of CO_2 .

- 6) Excluding the apparently anomalous 11.92 result for the Room Temperature test, the air dried samples showed an average .68 kg/cm^2 strength increase for the 7 day period (7-14) and a 1.49 kg/cm^2 strength increase for the subsequent 14 day period (14-28); i.e. approximately twice the previous increase, or an amount consistent with a steady CO_2 uptake and CaCO_3 formation.

While it may be premature to place much faith in this apparent strength increase with time, it certainly seems promising. Data presented in Table 5, Appendix B for flume samples are also reasonably consistent with these results and interpretations.

9.3.4 Clay Bonding Influence

As discussed in section 6, soil composed of "cohesive" clay, silt and sand could be expected to have some shear strength due to the tendency of clay to act as a binder for the silt and sand grains.

Once the oil sands clays have been rendered "cohesive" rather than "dispersive", the soil mixture should have an inherent shear strength consistent with Figure 6.1. Since oil sand tailings could conceivably be intermediate in size distribution between the particular sandy clay and silty clay identified in Figure 6.1 (rather than where shown in Figure 6.1), a UCS of from 2 to 10 kg/cm^2 might be possible for the material.

Some portion of the initial shear strength of the material is thus likely to be due to the "natural" bonding effect of the clay.

The extent to which lime can produce bonding over and above this effect should be determined. This could be done by dewatering a sample of sludge, in a centrifuge, mixing it with an appropriate amount of sand and then determining the shear strength (if any, or if possible) of the resultant material.

As the lime treatment results in a continuing strength increase, with time, the phenomenon studied here must be more than just normal soil cohesion.

9.4 Geotechnical Design Implications

It is anticipated that the bulk of material treated in a commercial disposal system would be deposited in, and remain under, saturated conditions. Hence, based on the results presented in Table 9.1, only minimal or no soil cohesion would normally be

(9.5)

obtained during operation. As it is probably simpler (and safer) for geotechnical design purposes to assume the soil has no inherent cohesive strength during construction in the wet condition, we have used such an assumption for conceptual disposal system design purposes. However, when the system dries out and is able to absorb air, it should develop significant shear strength.

More test work would obviously be useful to show how reproducible this effect is prior to making any assumptions about the long term strength improvements which may be obtained, but the results are certainly promising.

Such testing might, perhaps, best be done by irrigating samples with a Na_2CO_3 solution to provide a controlled level of $\text{CO}_3^{=}$ rather than waiting for the sample to absorb atmospheric CO_2 .

Figure 9.1

TGA of Limed Tailings

Date: 12-Apr-83 Time: 9:38:23
 File: ZENON.10 ASHOK#5
 Operator:

Sample: L
 Size: 20.72 mg
 Rate: 20/MIN AIR

TGA



(9.6)

(9.7)

TABLE 9.1

UNCONFINED COMPRESSION STRENGTH OF CURED WHOLE TAR SANDS
TAILINGS SEDIMENT TREATED WITH LIME AND LIME PLUS POLYMER

UCS - Kg/cm ²									
Coagulated with 900 mg/l CaO and 8 mg/l A-110						Coagulated with 3000 mg/l CaO			
Room Temperature				69°			69°		
Elapsed	air	humid	saturated	air	humid	saturated	air	humid	saturated
Time/Days	dry	air		dry	air		dry	air	
0	7.05								
7	8.87		2.59	9.63	9.06	1.39			
14	10.86	8.87	5.82	9.70	10.07	4.20	5.64	5.13	3.81
28	11.27	12.47	5.59	11.64	10.07	3.23	-	5.08	-
190	6.82	5.08	*	7.77	6.10	*	-	2.39	-

* Specimen disintegrated.

(9.8)

TABLE 9.2

UNCONFINED COMPRESSION STRENGTHS OF VARIOUS SOILS AND ROCKS

	Kg/cm ²
Soft Sand	.25 - .5
Medium Sand	.5 - 1
Stiff Soil	1 - 2
Very Stiff Soil	2 - 4
Extremely Stiff Soil	4 - 6
Strong Soil	6 - 8
Very Strong Sand or Extremely Weak Rock	8 - 10
Very Weak Rock	<12.5

10.0 PROCESS WATER RECYCLE

The extraction process and current tailings disposal operations have a number of major constraints which dictate many attributes of the processing technology. Most of these were discussed in Sections 3 and 4, which should be reviewed if the reader is not familiar with this technology.

Water is the lifeblood of the extraction process. While extraction is very tolerant of what, in other industries, might be described as very poor water quality, both water quality and immediate availability of large quantities are important to its proper performance, especially during processing of poor, high fines oil sand.

Recycle of process water occurs over at least 22 of the 25 year design life of the plant. Any new tailings treatment technology affecting the process water, especially if it results in a higher amount of recycle, needs to be carefully compared to the process requirements, particularly over the long term. Because of the potential buildup, over the years, from the recycle of dissolved and suspended contaminants in the process water, a predictive capability for the time dependent future levels of contaminants is essential to evaluate and maintain process efficiency. With such recycling and other interactions which occur between processes in the plant, the predictive capability needed is best handled by a computerized water balance model.

In fact a computer model has been implemented to achieve such predictive capability, one which models an existing Syncrude type oil sand plant water system; it is also possible to superimpose on this model the water related effects of the lime/polymer tailings treatment technique, as a special case.

In the discussion which follows, general water modelling concerns are discussed first, then analyses, data and assumptions in the construction of the model. A micro-computer "spread sheet" type program "Report Manager" has been used for the modelling because of its ease of implementation and flexibility. The model runs under the MS-DOS operating system and is similar but more powerful than better known programs such as Multiplan, EasiCalc, SuperCalc, VisiCalc and a variety of other such spread sheet programs. The program is discussed in detail in Appendix C.

Following the discussion of the model and test results for related water handling, a discussion of the significance of the water treatment work which has been done is presented.

10.1 Modelling Concerns

One of the major factors in process water operation (and modelling) is to decide when and how much water to recycle from the pond. Figure 10.1 illustrates the distinct zones which form in tailings water as it settles. It is usually assumed that tailings need to be settled for about three years before a sufficient volume of clear water develops in the pond to allow recycle of relatively low suspended solids water to the extraction process. A maximum recycle of 65% of the total extraction water consumption rate is anticipated. This was the case at Suncor, but Syncrude, with 10 times as much pond area was able to recycle water sooner and has reportedly occasionally sustained levels as high as 100% recycle for the extraction plant water requirements.

Figures 10.1 and 10.2 illustrate the water "profiles" for the conventional tailings pond and the clear water formed in the chemical treatment process. The program models only the "A" zone shown in either figure. It does not deal with the solids content of this zone, or model interchanges with other zones, which were judged to be much less significant concerns.

10.1.1 Seasonality

A number of characteristics of pond water, such as the suspended solids and volatile organics levels are known to vary with the seasons. When Syncrude's pond is covered with ice in midwinter, it is much more quiescent and suspended solids levels can decline to less than .1% on recycle water, versus perhaps .9% on recycle water in the summertime. The ice cover can also tend to trap the volatile naphtha contained in the dilution centrifuging tailings. For this reason, levels of T.O.C. may increase by 30-40 mg/l (due to this volatile fraction) in the wintertime.

These seasonal effects are not currently considered in the computer model, as they are also viewed to be of minor significance. The material balance model assumes steady ongoing operation (it does not model the three year start-up situation in which no recycle water is produced).

10.1.2 Recycle Level Assumptions

A key model limiting condition made is that the cumulative amount of recycle water never draws the clear water layer volume below a prescribed minimum. The settling rate and production rate of decant water need not be considered, provided the clear water volume is not drawn down at a rate which would deplete the A-zone,

i.e. below the base of the A-zone in Figure 10.1. With this assumption, the volume of "clear water available" can be considered to be growing at a relatively steady annual rate, proportional to the total volume of tailings being produced. (The accuracy of this "clear water volume available" prediction could be improved by incorporating a settling rate model in the material balance calculation, but for the purposes of evaluating water chemistry it is not needed.) The volume of clear water ultimately produced from chemical treatment appears to be consistently greater than for conventional disposal, but exact levels at field conditions need to be confirmed. 80% has been assumed in the calculations, based on an average void ratio of about .7 for the settled solids (see section 8.0).

Actual plant operating strategy is typically one of two methods: recycle at a fixed rate (i.e. 50%) or recycle at the maximum possible rate that can be sustained for extended periods of time at a level of solids in the water which might be considered a maximum or target value.

This strategy can be modified to serve as a long term operating strategy, but recycle levels on a month to month basis would typically be set by pump speed rates to a fixed percentage (say 65%) of the extraction water used. In actual practise, unless a safety margin of clear water is allowed under the pond water recycle barge, at high draw down rates the settled solids interface height would become unstable. The recycle barge would draw variable amounts of water from the settled solids zone (Zone B in Figure 10.1) in the pond causing fluctuating recycle water solids contents.

Most of the other factors significant to the accumulation of contaminants in the pond water are either dependent on the grade of oil sand, which is determined primarily by nature, the plant operating conditions, or the recycle rate of the pond water. The amount of water recycled is thus, the most critical independent variable.

10.2 Water Model with Chemical Treatment

The same basic concepts, described in sections 3, 4 and here can not only be used to model and predict Syncrude type extraction, tailings disposal and water recycle parameters, but with minor modifications can be and have been applied to the chemical treatment system. The major changes are allowing for a higher percentage of recycle water available from the process and reflecting the chemical interactions of the lime. Most of the other parameters of the lime treatment process affecting the water composition, such as the percentage of solids in the recycle water or the temperature, are a function of the equipment/disposal

(10.4)

system design, and could, as needed, be modelled in a manner which accommodates the differences between the existing and the lime treatment disposal systems. This level of sophistication has not proved necessary.

In most of the discussion which follows, the reader should refer to Table 10.1, which presents the model results for the existing Syncrude disposal system. Table 10.2 presents the system as it would look with lime addition beginning in 1988. Unless otherwise stated, the two systems are assumed to be the same relative to the water balance.

10.3 Oil Sand Input Parameters (Both Models)

The rate of feed of oil sand to the extraction process, the bitumen, water and solids content of the oil sand and the mineral and connate water composition are all taken as parameters which are independent. The oil sand throughput is a function of the plant design and operating practise while the other parameters are inherent in the oil sand deposit itself. The values used have been assumed as constants, or as data are available and as they are known to vary in practise. (The model will account for any such variability if the appropriate data is available.) For the time being, lacking comprehensive year by year data for Syncrude or consistent data for any other plant, for fines composition or connate water quality, the values indicated have been assumed from published information. If it were possible to obtain or generate these values on a year by year basis, it would significantly improve the predictive capability of the model.

10.4 Operating Parameters

The level of both caustic and water, used in the extraction process, are controlled by the extraction plant staff, primarily in response to the oil sand grade. Lower bitumen, higher fines oil sand tends to require both higher caustic and water levels for smoothest and most efficient operation; perhaps double average levels (e.g. see E.R.C.B., 1984). Lower recovery efficiency results despite careful attention to such process changes. The NaOH and overall water consumption rate are considered as operator controlled independent values in the program. They are currently set to average values.

The level of sodium in the connate or mine depressurization water is significantly higher than the level which might be expected for sea water type Na:Cl ratios; i.e. the inverse ratio at 1.16:1 versus 1:1.17 meq/l:meq/l respectively, reflecting the presence of a number of other significant anions in these water streams. These

are primarily such species as sulfate and bicarbonate, discussed in subsequent sections.

10.4.1 Chloride

Chloride (Cl^-) is a conserved species (meaning it enters the process in the water phase and stays there without reacting) and is an excellent "marker" for concentration/dilution effects throughout the water system. The principal sources of chloride in the tailings pond water are the oil sand connate and mine depressurization water. Connate water averages around 4.4% of the oil sand weight and is highly variable as to its weight percent of the oil sand and salinity (thus chloride) in-situ. Where all mine depressurization water is pumped to the tailings pond, (as was planned by Alsands, it has been done to only a limited extent at Syncrude) there may be a significantly greater chloride input to the tailings pond than is currently assumed in the model.

At high levels (perhaps above 1500 mg/l, Lane's opinion only), chloride may interfere with the extraction process. As discussed in Section 3.0, it can reduce bitumen recovery and froth quality in extraction, leading to significantly reduced extraction efficiency. When the water model indicates levels of chloride of 1500 ppm or greater in operation, control measures, such as discharging a bleed stream from the process, may be warranted. These control techniques are discussed in section 10.11.

Suncor's oil sand connate and mine depressurization water are essentially fresh, containing much less chloride than Syncrude's. Presumably, either the depositional environment was fluvial, rather than "oceanic", or the regional hydraulic head has resulted in a "rinsing" of Suncor's area of the Athabasca deposit by natural precipitation and ground water flow into the Athabasca River (most likely). There are some indications that the salinity of mine depressurization water is increasing at Suncor.

In any event, Suncor's connate water can be considered to have a much lower chloride level, not likely to ever be a problem for the extraction process.

Salinity and particularly chloride, is the major concern for the chemical treatment process. Although good data for the most critical factor, oil sand connate water composition and amount, is not available, we have "guesstimated" a worst case of current (apparent) levels increasing to 6500 ppm chloride at 10%/year. 6500 mg/l chloride seemed to be an average level for mine depressurization water, and, it is believed, represents more or less an upper limit for connate water salinity.

Using the maximum level of recycle which could conceivably be

(10.6)

obtained with chemically treated tailings and the highest level forecast for connate and mine depressurization water, the levels of chloride attained are in the "danger zone" towards the end of the project life (actually somewhat past the "normal" 25 year life, at about 30 years). However, these predicted worse case values would suggest that the water salinity would probably not be a concern for extraction.

The obvious control strategy in such an eventuality is to discharge a greater position of mine water to surface drainage.

10.4.2 Sodium (Na^+)

Sodium (Na^+), as for chloride, is also in relatively high concentration in the connate and mine depressurization water at Syncrude (but not as much at Suncor). The sodium hydroxide added as a process aid also may contribute as much as 40% of the Na^+ levels in extraction tailings and the pond water.

Na^+ is described in MacKinnon, 1981 as a "conserved" species in the tailings ponds. However trial and error comparison of model results with reported values, seems to indicate the possibility of some interchange of Na^+ in the system. It is suggested that some Na^+ may react with bitumen derived organics (as a surfactant) and or the clay (as an exchangeable cation) in the process. It might then be withdrawn from the water phase into the bitumen in the extraction process or the tailings pond, or settled with the sludge clays. Currently available information is not sufficiently accurate on this point. A further investigation may be warranted, but the upper limit for this phenomena is a 50 to 60 mg/l (probably much less) annual reduction in the Na^+ level from what might otherwise be predicted.

10.4.3 Sulfate (SO_4^{--})

Sulfate would also be considered a conserved species in the tailings pond except for the apparently anomalous variation with depth. Perhaps this is an indication of biologically active sulfur (S) compounds.

The available information on Syncrude's tailings pond and connate water concentrations suggests a major source of sulfate, other than connate water, for Syncrude. It is known that alum (aluminum sulfate, $(\text{Al}_2(\text{SO}_4)_3)$ and sulfuric acid (H_2SO_4) are used in boiler-feed water treatment, and blowdown, ultimately building up in the tailings pond. Also, effluent from sour water, produced in the upgrading process, contains significant levels of sulfate

and some sulfide. In total, these streams probably account for in excess of 80% of the total sulfate ultimately retained in the pond.

Because Suncor's process water (utilities and upgrading) is treated and discharged to the Athabasca River, and there is much less salinity in their connate water, the accumulation of sulfate in their pond water is considerably less (Jantzie, 1977).

10.4.4 Bicarbonate (HCO_3^-)

A major source of HCO_3^- in the pond is the oil sand connate water. However, there are other sources which might be significant such as aeration in the extraction plant, absorption of CO_2 by the tailings pond, and in the makeup water, among others.

The aeration occurring in extraction secondary recovery, into an alkaline solution, should result in absorption of virtually all the contained CO_2 of about 230 ppm from the atmosphere and could theoretically contribute 100 to 400 mg/l/year to the total tailings water. This process alone would continuously sustain significant increase in the overall concentration of HCO_3^- being circulated in the water system.

Calculations indicate that, despite its huge area, absorption of atmospheric CO_2 in the tailings pond probably accounts for less than 1.0 mg/l/year addition from this source. Other sources such as utilities and upgrading might well contribute to a significant annual increase in the pond or recycle water concentration level, of perhaps 100 mg/l/year.

10.5 Effects of Lime on the Water System

10.5.1 Effect of Lime on Bicarbonate (HCO_3^-)

When lime is added in the chemical treatment process, the effect of the Ca^{++} will be, as discussed in section 7.0, to first precipitate out of solution essentially all HCO_3^- in the lime treated tailings water, see Table 10.2. As a result, a proportionately higher consumption of lime is expected for the initial period. If lime addition were incorporated into an existing plant, it would have the effect of, within the initial years of operation, greatly reducing the bicarbonate in the recycle water. The steady state level would eventually be reached, equivalent to the amount of new bicarbonate, actually entering and produced in the process water system at any one time, perhaps 100 mg/l. This itself would consume 90 mg/l CaO , (i.e. there would be

(10.8)

no accumulation).

Because of the huge quantities of water consumed, bicarbonate can represent a major consumption of lime. (Perhaps 400-600 mg/l of the total lime consumption of 800-900 mg/l in the experimental work was due to bicarbonate removal.)

10.5.2 Calcium (Ca^{++})

Because of the high inputs of HCO_3^- as well as extensive aeration throughout the system, calcium is normally present in tailings and extraction water at levels consistent with the solubility of CaCO_3 , or about 6-8 ppm. (It is readily precipitated in the presence of excess air derived CO_2 to these levels). Slight increases above these levels from calcium addition to a process stream would probably result in a fairly rapid reduction to these levels by CO_2 absorption into the water system.

Addition of relatively large doses of Ca^{++} in the form of CaO or Ca(OH)_2 , to the water system as used in the lime treatment process changes the balance of several ionic species (as well as the charge character of the clays). Dissolved Ca^{++} first reacts with all the available HCO_3^- in solution to precipitate CaCO_3 , i.e:



When essentially all of the available HCO_3^- has reacted and been removed, the residual Ca^{++} initiates an ion exchange process with the clays as discussed in Section 5.0. Free Ca^{++} ion, because of its higher charge density, displaces Na^+ and some K^+ from the ion exchange sites of the clay particles, though probably not stoichiometrically.

10.5.3 Reactions of Ca^{++} With Ion Exchanging Clay Minerals

Cation exchange capacities have been measured (separately) for clay minerals, at about 5 meq/100 g, typical of sandy soils. Other minerals such as quartz are relatively inactive at levels of Ca^{++} of a few mg/l.

Even if the data for the minerals distribution in the oil sand deposit were available, it might not be very helpful. The main problem is that to be useful, exchange capacities would need to be related to levels of at least two reactive clay minerals, kaolinite and illite. A problem of predictability results as these minerals have significantly different exchange capacities and the

concentrations are known to vary widely over short horizontal and vertical distances in the deposit.

10.5.4 Preferred Ca^{++} Addition Control Strategy

To develop a predictive capability based on mineralogy and water quality it would be necessary to measure the exchange capacities of the individual clay components commonly present and then verify that the individual clay exchange capacities are additive i.e. not affected by, or competing with other components in the tailings system. It would also be necessary to analyze levels of clay minerals in the tailings samples which have been used in the investigation. Extensive clay analyses are difficult, slow and expensive by X-ray diffraction (and are outside the scope of this study). Even if these compositions could be measured under field conditions, or on an on-line basis, the control of the lime addition rate from such mineral analyses would present problems.

It is suggested that a preferred addition control strategy would be a Ca^{++} ion specific electrode, on the excess residual Ca^{++} in solution. It is also possible that a simple strategy of pH control for lime addition might be effective.

10.5.4.1 Threshold Detection Limits

A second reason why mineral analyses do not present a good opportunity for monitoring the progress of calcium reactions, is that Thermal Gravimetric Analysis (T.G.A), Thermal Differential Analysis (T.D.A) and X-Ray Diffraction (X-RD) have been tested in conjunction with the stabilization investigation to identify new minerals formed by reaction of the clays with Ca^{++} . As described in Section 9.0, due to the apparent low levels of minerals relative to the resolving power of the different machines and possible interference from bitumen cracking reactions, these studies have not been very conclusive.

10.5.5 Cation Exchange Consumption of Ca^{++}

Cation exchange capacities of individual minerals should however, still be investigated, as they are crucial to the process. Values of cation exchange capacities for a variety of clay minerals were presented in Table 5.1, and have been measured for the tailings at about 5 meq/100g. Assuming a 65/35 kaolinite/illite ratio (a typical value) for the clays, and typical levels in our tailings (about 5 wt % of the solids) observed Ca^{++} consumed in the process is consistent with the known chemical reactivity of the

(10.10)

pond water and the levels of exchange capacities normally found with these minerals. The clay mineral system is saturated with sodium from NaOH addition but has had little previous contact with Ca^{++} . The observed exchange capacities appear consistent on the high end of the range for the minerals present. This also needs to be confirmed.

10.5.6 Organic Consumption of Ca^{++}

Some organics, when present, could precipitate Ca^{++} from solution by formation of organo-metallic chelates or soaps. The extent to which it is occurring has been estimated at as much as 190 ppm Ca^{++} on total tailings.

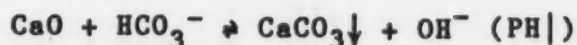
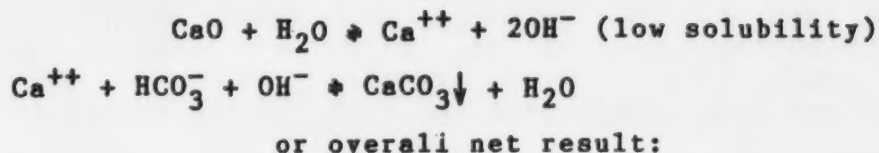
10.5.7 Alternative Ca^{++} Addition Control Strategies

Other methods of control of lime addition such as coagulated slurry viscosity or methods of measuring settled density "on line" should be evaluated for process control purposes. Residual Ca^{++} by ion specific electrode, or pH may be simplest, but as can be seen from the discussion of other Ca^{++} consumers, may not be a direct indication of the intended geotechnical results.

10.6 pH/Hydroxide (OH^-)

Section 3.0 discussed the role of pH/NaOH in control of the extraction process.

Lime addition results in an increase in the pH, even when no calcium remains in solution, as follows;



With this reaction, and the calcium/clay ion exchange reaction occurring, i.e.:



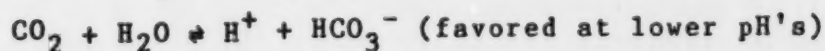
The net effect on the water chemistry of liming tailings is thus to increase the concentrations of both Na^+ and OH^- in the process recycle water (by as much as 200 mg/l for the OH^-). The normal level of NaOH addition, as a process aid, equates to an

(10.11)

increase of about 170 mg/l in the Na^+ level. It is however, usually added mainly for poorer quality oil sand and in considerably higher quantities than the average values indicated above. Higher grade oil sand can be processed, at least at Suncor, without any caustic addition. However, there is little published data available on the effect on extraction of excess caustic, although it is reputed to cause emulsion problems.

It is believed that the higher levels of Na^+ and OH^- produced by liming can be dealt with in at least five ways:

- 1) By defining and operating at the maximum caustic level for the extraction process operation, rather than the current strategy of maintaining the minimum caustic level.
- 2) By recarbonation of recycle water with air or CO_2 (which could come from the original limestone calcination for lime production), or a combination, to an acceptable pH.



- 3) By maintaining separate holding ponds for recycle water which has been recarbonated and pH reduced and for recycle water at high pH. By combining these streams in appropriate amounts, process control could be maintained without deliberate NaOH addition.
- 4) The extraction feedwater pH might also be controlled by adjusting the pH "on-line" to that required with a small amount of sulfuric acid or sour water derived from upgrading. This alternative has not been evaluated in detail.
- 5) By further research on the liming process aimed at minimizing the addition of CaO (and consequent production of OH^-) on an operating basis. (i.e. perhaps more polymer and less lime or deliberately allowing some segregation.)

In particular the ability to recarbonate with CO_2 , for pH reduction, followed if necessary by gas stripping for CO_2 removal (reheating of process water will, in itself cause some CO_2 stripping). An excess of CO_2 in the water phase if not removed, would however, result in some increase in the CaO consumption when recycled through the extraction plant. Current estimates indicate that a steady 65 mg/l HCO_3^- would be created by this type of control strategy, whereas HCO_3^- in untreated tailings is steadily increasing.

The optimum hydroxide control strategy may be one that combines

two or more of these methods. Further research is required.

10.7 Process Water Quality Control Considerations

One of the major current uncertainties with the use of the tailings treatment process is not related to liming, but to the levels at which salinity, (chloride), sulfate and other contaminants might affect the extraction process. It is possible Syncrude might encounter this type of problem with the current mode of operation before the end of the project life. Liming differs only in that the rate at which the problem may develop into a situation requiring action is faster, due to the higher recycle level, and might require control measures sooner, if they were required at all.

There are several ways to control this buildup, if necessary. The easiest is to discharge to surface runoff a larger proportion of mine depressurization and run off water (i.e. the discharge to Poplar Creek in Syncrude's case). The next simplest is probably to "bleed" a portion of the water stream which is then treated to surface water quality criteria and released to the environment.

10.7.1 Surface Water Discharge

Assuming that discharge of process water within the quality standards indicated in Table 10.3 is environmentally and politically acceptable (it has not been in Syncrude's case), process contaminant buildup control could be achieved, if required, by a bleed stream equivalent to perhaps 15% of the total water requirement of the process, illustrated in Figure 10.3. Because the product of the tailings treatment is a clarified high pH water, pH reduction and detoxification would be the minimum required. As pH reduction to meet surface water discharge standards may also contribute to detoxification, treatment of the bleed stream would likely be relatively inexpensive.

A rough cost estimate for carbon absorption toxic organics treatment is about \$9 million/year, but this expense would not be encountered until towards the end of the project life - if at all.

Even if not required for minimizing contaminant buildup, detoxification to eliminate the accumulation of process water after project termination will still be required.

10.7.2 Recycle to the Process

Assuming that excess salinity is the main concern for process water recycle, desalination of a portion of the stream to allow recycle could be at least a technically feasible alternative for controlling the contaminant buildup without surface discharge. Desalination is usually obtained with techniques such as reverse osmosis and is relatively expensive. Perhaps it might be possible to utilize the extreme cold of winter in the area to produce high purity water by a "freeze-thaw" desalination and solids removal in a ponding technique such as illustrated and described in Figure 10.3.

The resultant concentrated saline water stream (after filtration) might be disposed of by deep well injection into a brine containing formation.

10.7.3 In-Situ Steam Quality

Water produced as a bleed stream from treatment of extraction recycle water would be of an excellent quality for production of steam for in-situ steam injection recovery of bitumen. The slight trace of suspended solids and dissolved silica would probably need to be removed and oxygen scavengers used to reduce dissolved O_2 . The pH may also need to be adjusted along with these relatively minor treatments. The water should be equivalent, or better than, water which has been processed through typical in-situ produced water recycle treatment systems.

The effluent water should have a value comparable to that resulting from fresh water treatment and handling. This potential bleed water disposal method warrants further investigation.

10.8 Preferred Water Treatment Configuration

A number of schemes for water handling for pH control and bleed water treatment, if needed, have been analyzed. Figure 10.4 is a schematic of the preferred method of handling recycle water and bleed water. While currently available information does not allow very precise estimation of the volume of bleed water, which might be needed, the type of treatment approaches which would be applied have actually been tested.

For further details of water treatment and detoxification studies, refer to section 2.0 and 3.0 of Appendix A.

These results suggest that, if necessary, water can be readily treated and discharged from the process in a technically, environmentally and (probably) economically acceptable fashion.

Figure 10.1

Conventional Tailings Pond Water Profile

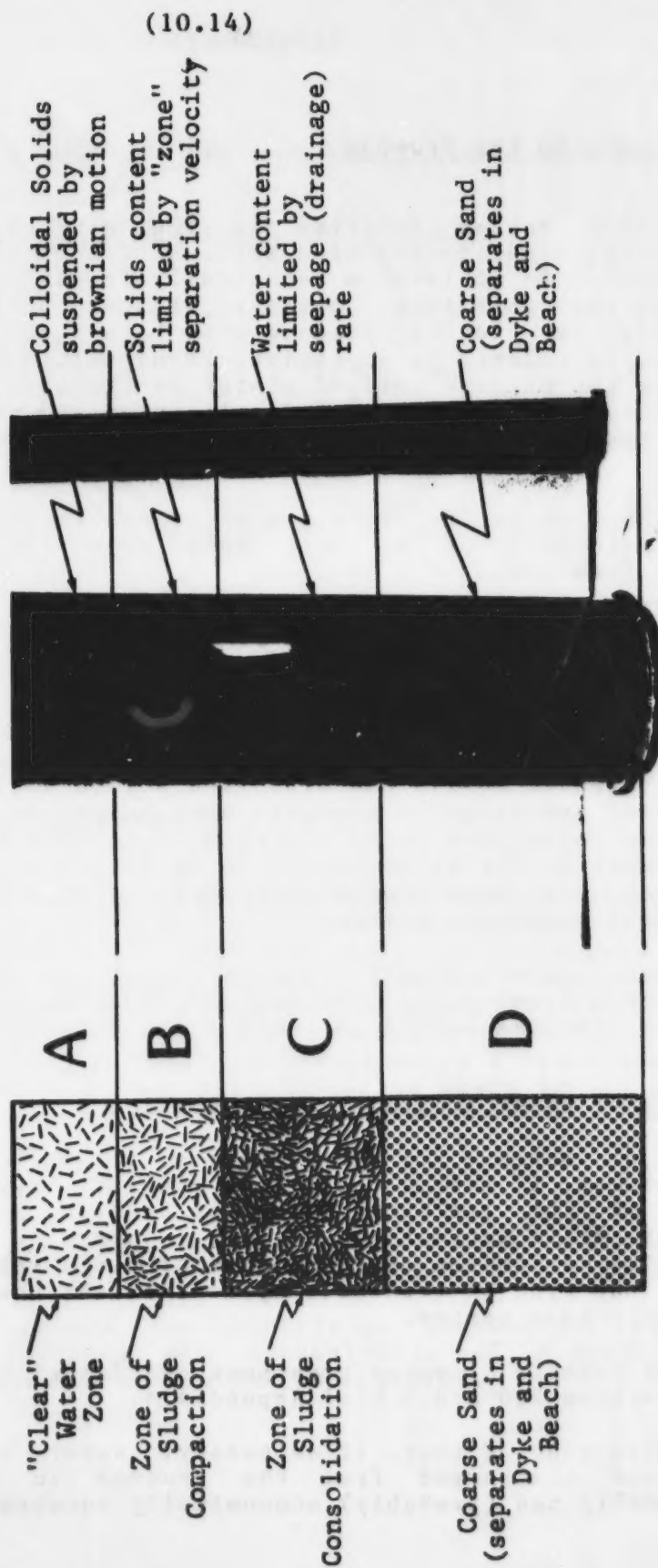


Figure 10.2

Chemically Treated "Whole" Tailings

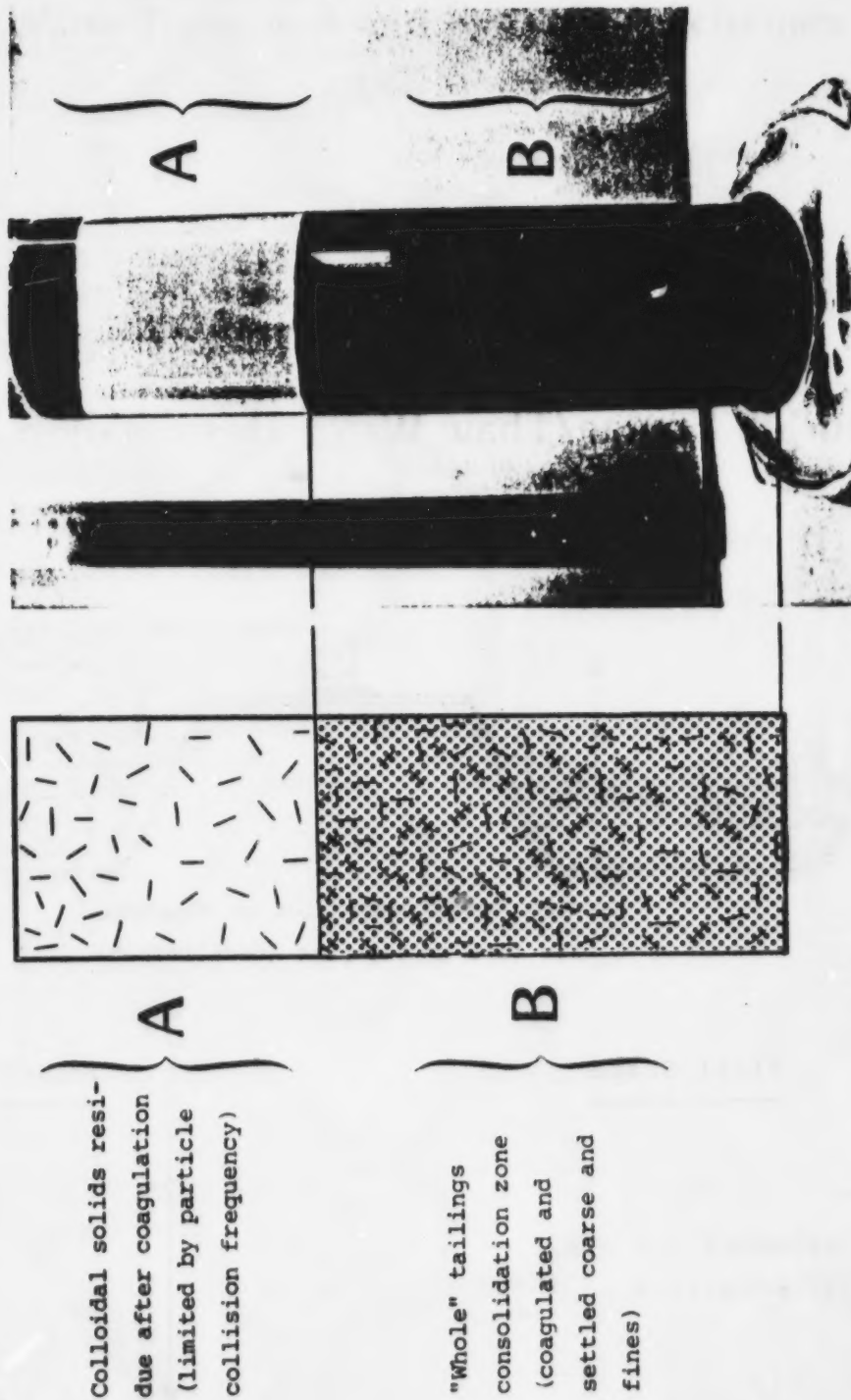
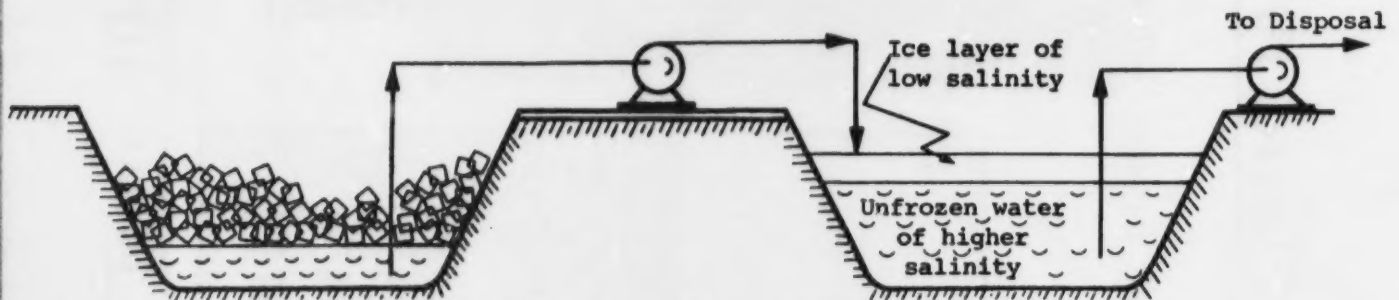


Figure 10.3

"Natural" Freeze/Thaw Water Desalination by Staged Ice Production in Two or More Ponds



Salt water pumped out to disposal.

Ice left in the pits (desalinized).

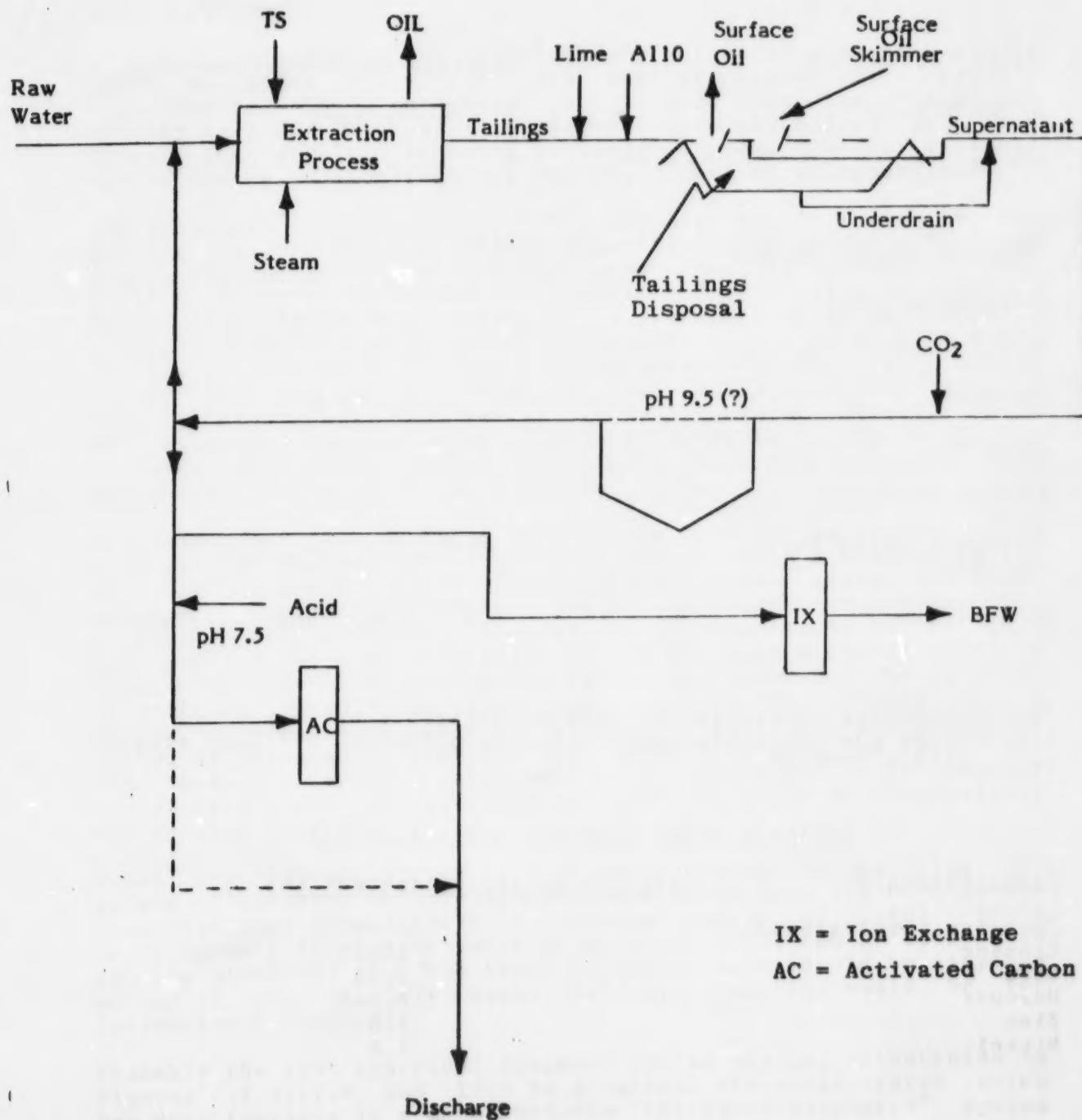
First Stage

Second Stage

(10.17)

Figure 10.4

Schematic of Suggested Water Treatment and Recycling Schemes



(10.18)

TABLE 10.1

Alberta Refinery Surface Water Quality Disposal Objectives

Water Contaminant or Constituent	*Average Concentration levels mg/l

Chemical Oxygen Demand	200
Oil and Grease	10
Total Suspended Solids	25
Phenols	1
Sulfide	0.35
Ammonia Nitrogen	12.5
Threshold Odour Number (Units)	300(?) Not Specified
pH (units)0	6.0 - 9.5(?) Not Specified

*Note: Average concentration levels obtainable by "best practicable control technology" based on a nominal effluent flow rate of 13.4 CGPM/MB.

Effluent Objectives for Toxic Elements

<u>Toxic Element</u>	<u>Net Concentration Values* (mg/l)</u>
Chromium (hexavalent)	0.30
Cyanide	0.025
Lead	0.10
Mercury	0.0005
Zinc	1.0
Nickel	1.0

11.0 CONCEPTUAL TAILINGS DISPOSAL SYSTEM DESIGN

From the workings of the process as understood so far, at least two basic design layouts should be practical. A third, more innovative but less proven method could also be evaluated in any subsequent work.

A new application of this approach would involve designing an oil sands plant to allow for much smaller out-of-pit disposal requirements. It also would incorporate into the design the ability to place tailings material back into the mined out area sooner than with the existing tailings disposal systems. Disposal system design implications are further discussed in Appendix B.

The principal consideration for the disposal system design is the bulking factor for deposited material. Because whole tailings represents the only solid waste with chemical treatment, the bulking factor is directly related to void ratio as shown in Figure 11.1. As the void ratio of low grade oil sands is typically slightly lower than high grade oil sand (a higher portion of fines is able to fill more of the interstitial volume) the bulking factor for a given void ratio is lower with a low grade oil sand than for high grade. Void ratios can be calculated directly from the extremes of tar sand grades illustrated in Figure 11.2 by assuming there is no other fluid (i.e. such as air or gas) than water and bitumen in the pore spaces.

The reader may wish to refer back to the void ratios determined in Appendix B. The results were almost always below a bulking factor of 1.21. The worst results were probably for low grade oil sand which is toward the higher end of the range measured for void ratios. As only a small portion of the oil sand would be at this low a grade and a major portion of the disposed material would be compressed under load, a reasonable average value for the material is probably around 1.10. (Note that one of the results was a nearly constant void ratio of about .56 consistent with a bulking factor of essentially 1.00 for high grade oil sand. The fact that the sample seemed relatively incompressible, is further corroboration that the material has been deposited at essentially the in-situ density.)

Using the bulking factor of 1.10 as an average design value, the volume of material to be disposed of, will be only 79% of that for a conventional scheme (with a bulking factor of 1.40). Since approximately five years worth of material (20%) can be backfilled to the mined-out pit, the total volume of material to be disposed of out of pit is only about 74% of what it would be for conventional disposal.

Probably the most practical disposal system design, illustrated in Figures 11.3, 11.4 and 11.5 is a central discharge system, which has many features in common with the "thickened discharge" system

(11.2)

in use at several Canadian mines such as Kidd Creek (Robinsky, 1978).

Either of the existing oil sands plants (Syncrude or Suncor), has completely different design considerations from a new plant. For Syncrude and Suncor, large existing dykes are already available which could potentially serve as containment areas for the fluid whole tailings as produced with the chemical treatment process. (Because these dykes also represent a significant investment for the oilsands plant operators, it is advantageous to make as much use of them as possible in any alternative tailings disposal technique.)

One of the primary concerns with application of whole tailings, treatment technology to the existing plants would be how the existing sludge which has accumulated to date could be permanently disposed. It is envisioned with the chemical treatment technique, that this may be accomplished by pumping some sludge out of the existing ponds and mixing it with whole tailings which when chemically treated will allow precipitation of all solids from the stream, including the recycled sludge.

Another major concern (or opportunity, depending on the perspective), is too site specific to be properly addressed here, but is the question as to whether the material can be used to backfill existing mine pits. This is certainly believed to be a major potential for the chemical treatment approach based on the current assessment of the potential for such uses.

Sections 11.2 and 11.3 discuss what we would expect to be the principal design considerations for application of the technology to both the Syncrude and Suncor plants.

11.1 New Plant Application of Dry Tailings Disposal

Figures 11.2 and 11.3 illustrate schematically how the technology might be applied to a new plant.

The principal design consideration for a new plant construction with tailings disposal based on the lime treatment process is that the amount of earth fill dyke construction be minimized. This is most easily achieved with a configuration that minimizes the amount of dyke volume required to contain the fluid tailings being disposed. The so-called "central discharge" system as proposed by Robinsky for containment of tailings by the "thickened discharge" system minimizes the amount of dyke required to contain a given volume of tailings. Figures 11.3, 4 and 5 indicate three possible configurations of a tailings containment area based on the central discharge approach and using either the material itself for construction of containment dykes or "hydraulic" sand from the tailings for construction of higher porosity and permeability dykes.

Preliminary estimates of the engineering design parameters for such facilities, at this stage of development work are not sufficiently precise to discriminate between the alternatives. Therefore it is suggested that all three of these design configurations be considered for further evaluation and subsequent scale-up testwork. The volume of material to be disposed of out of pit is estimated to be about 74% of the current out of pit volume. This value has been used in the economic evaluation in Section 13, but it should be stressed that the values based on laboratory work to date have a range of plus or minus about 30%. Should it prove possible to reliably repeat the conditions which demonstrated a bulking factor of 1.00, the out of pit volume required would only be 64% of that currently experienced.

11.2 Syncrude (Existing Plant) Application

Principal design concerns for application of dry tailings disposal technology to the Syncrude plant are that containment dykes are in place for the existing tailings pond, and placement of as much of the waste sand in the mined out area as possible will minimize the wastage of oil reserves and associated out-of-pit disposal problems. Only a portion of the existing dyke area needs to be used as a containment structure for the initially fluid whole tailings being deposited with the lime treatment approach, and this would logically be the area overlying the least oil sand. Further analysis of this option should look at the thickness and grade of any oil sand underlying Syncrude's tailings pond, if possible.

11.3 Chemical Addition and Mixing

Based on the conclusions in Sections 7 and 8 that air entrainment in our samples caused serious segregation problems, we felt that the only type of chemical addition technique that should be considered for commercial application should be those which exclude air from the mixing process.

The three principal types of chemical addition technique which meet these criteria are:

- 1 & 2. In-Line Mixers (static or motorized),
3. Lime slurry or polymer injection immediately ahead of or into the casing of a centrifugal pump.

The use of a centrifugal pump as a mixer has inherent cost advantages, but as an apparently untried application, would require pilot scale testing to demonstrate its technical and economic feasibility.

(11.4)

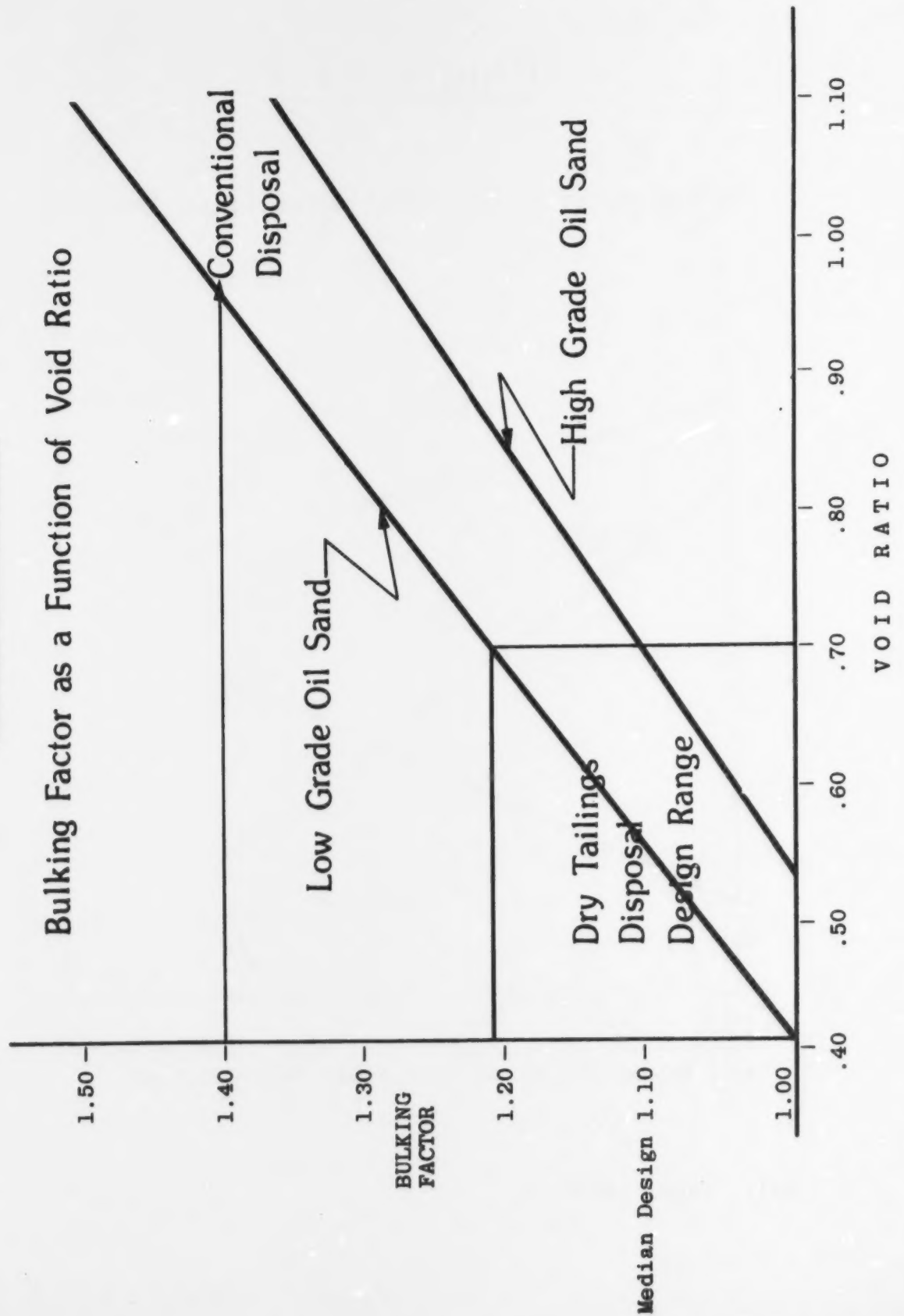
The in-line mixing arrangement, is basically a conventional mixing approach using well proven in-line mixing apparatus.

11.3.1 Allowance for Mixing Time

The residence time for whole tailings after lime addition at the velocities which would be required for pumping the treated slurry are such that mixing times approaching those which provided optimum results in the laboratory tests should be feasible. However, the in-line mixing times will change as a result of relocation of tailings lines and disposal at sites in proximity to the plant or at some distance away from it. As discussed in Section 9.2, this is unlikely to be a problem for the properties of the deposited material and hence no special effort has been made to ensure uniform residence time in the pipeline for subsequently deposited material. The ability to pump the coagulated slurry from extraction to tailings disposal at significantly lower velocities should result in appreciably lower capital and operating costs for pumping and tailings lines. These are addressed in section 13.0.

These three alternatives and any other methods of disposal which allow for a week or so of drainage before construction begins should be further investigated.

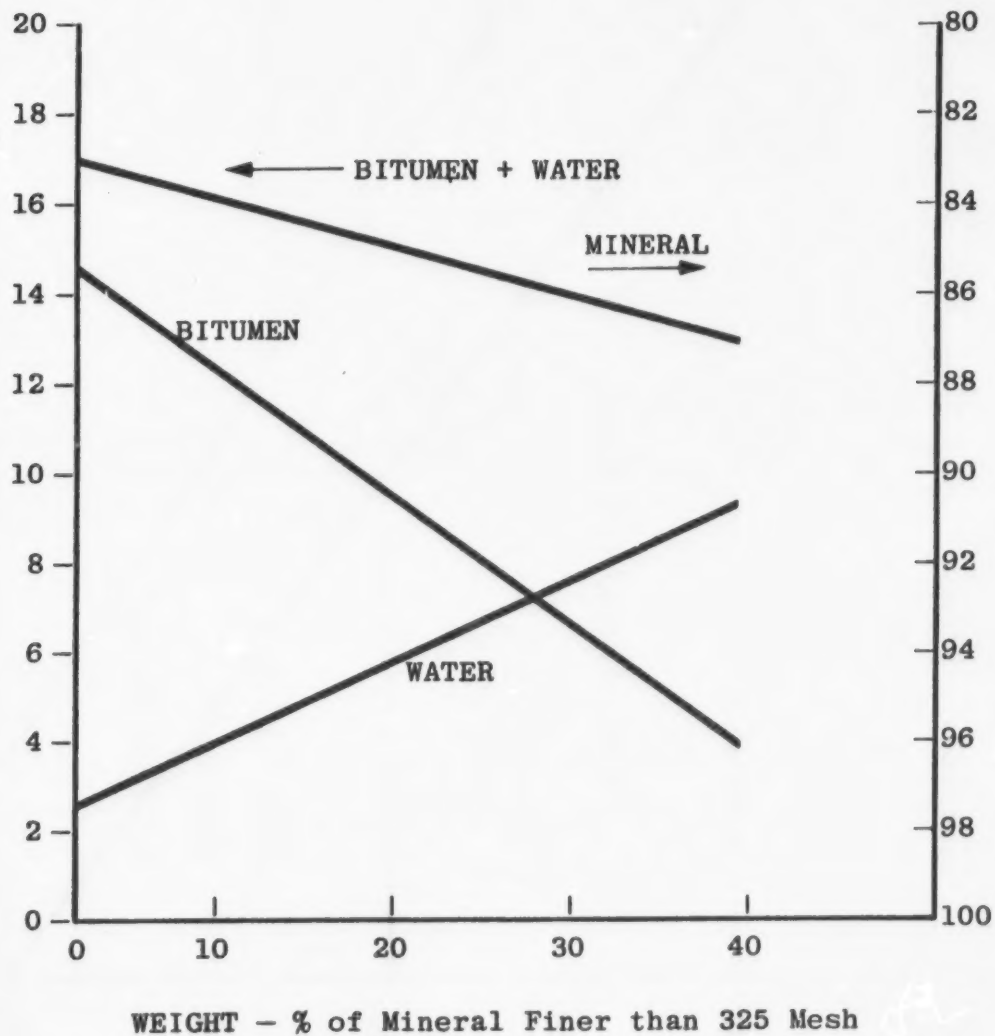
Figure 11.1



(11.6)

Figure 11.2

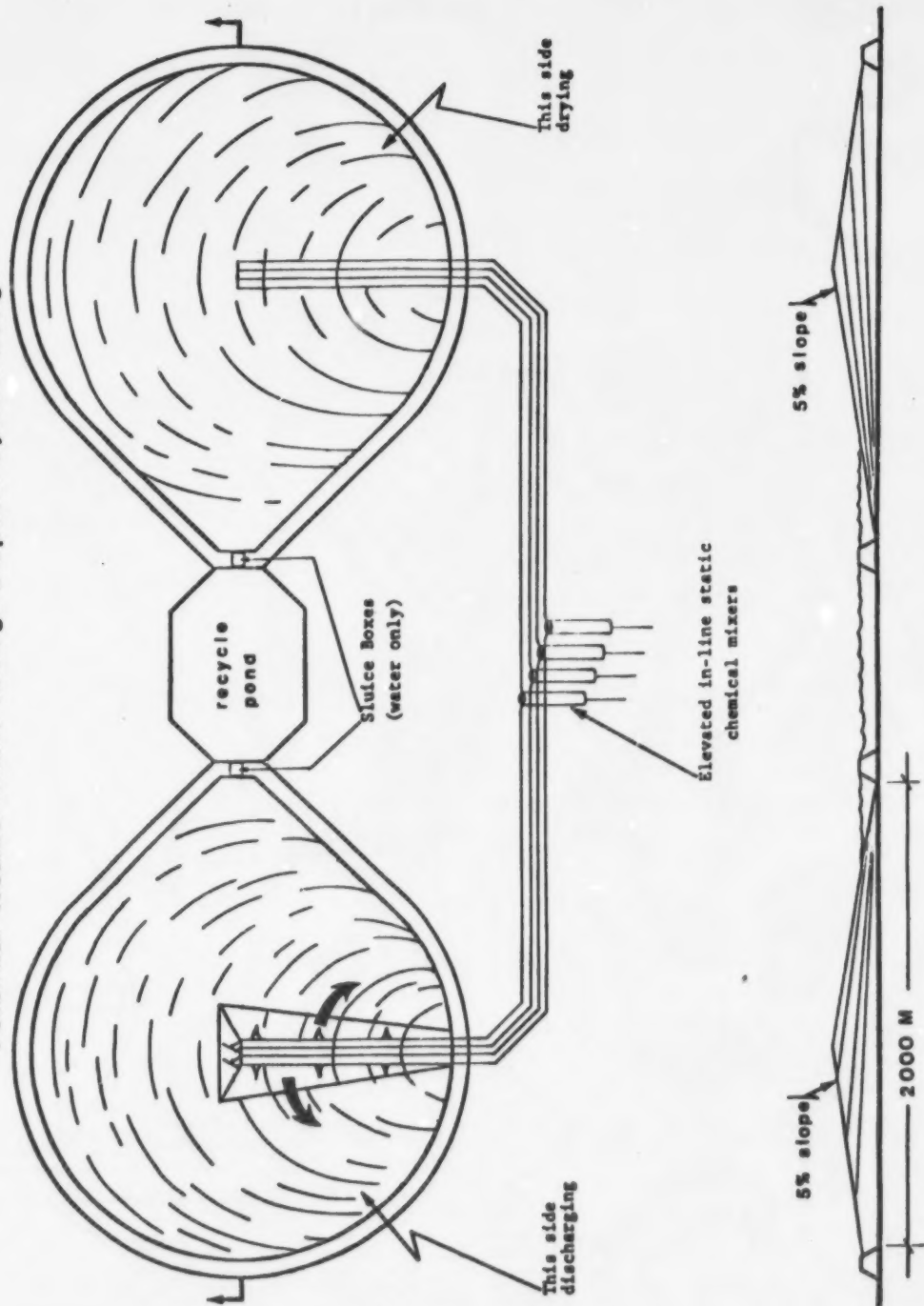
Relationship of Bitumen, Water, Fines Content



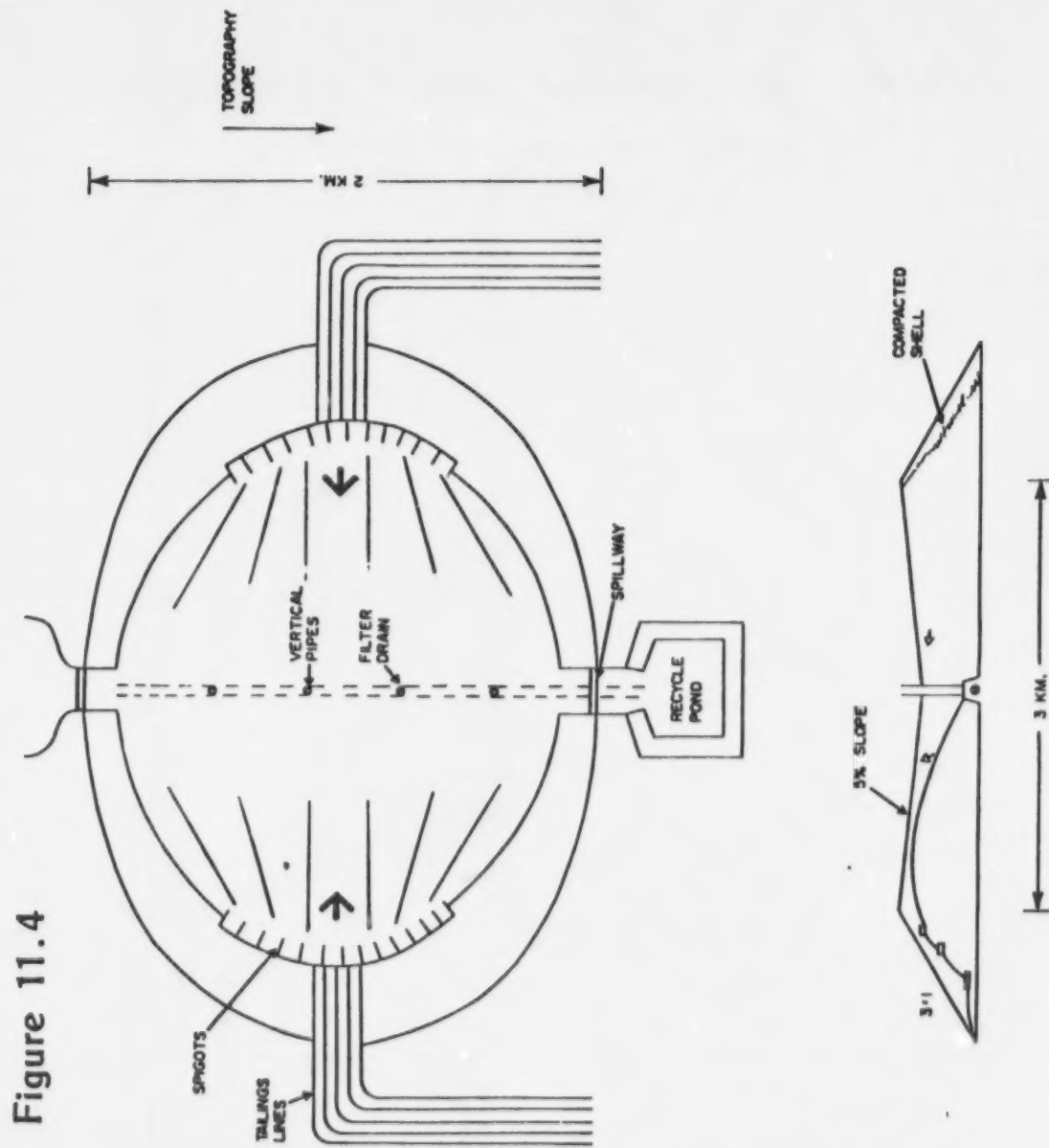
Ref: Camp, 1974

Figure 11.3

Potential Treated Whole Tailings Disposal System Design



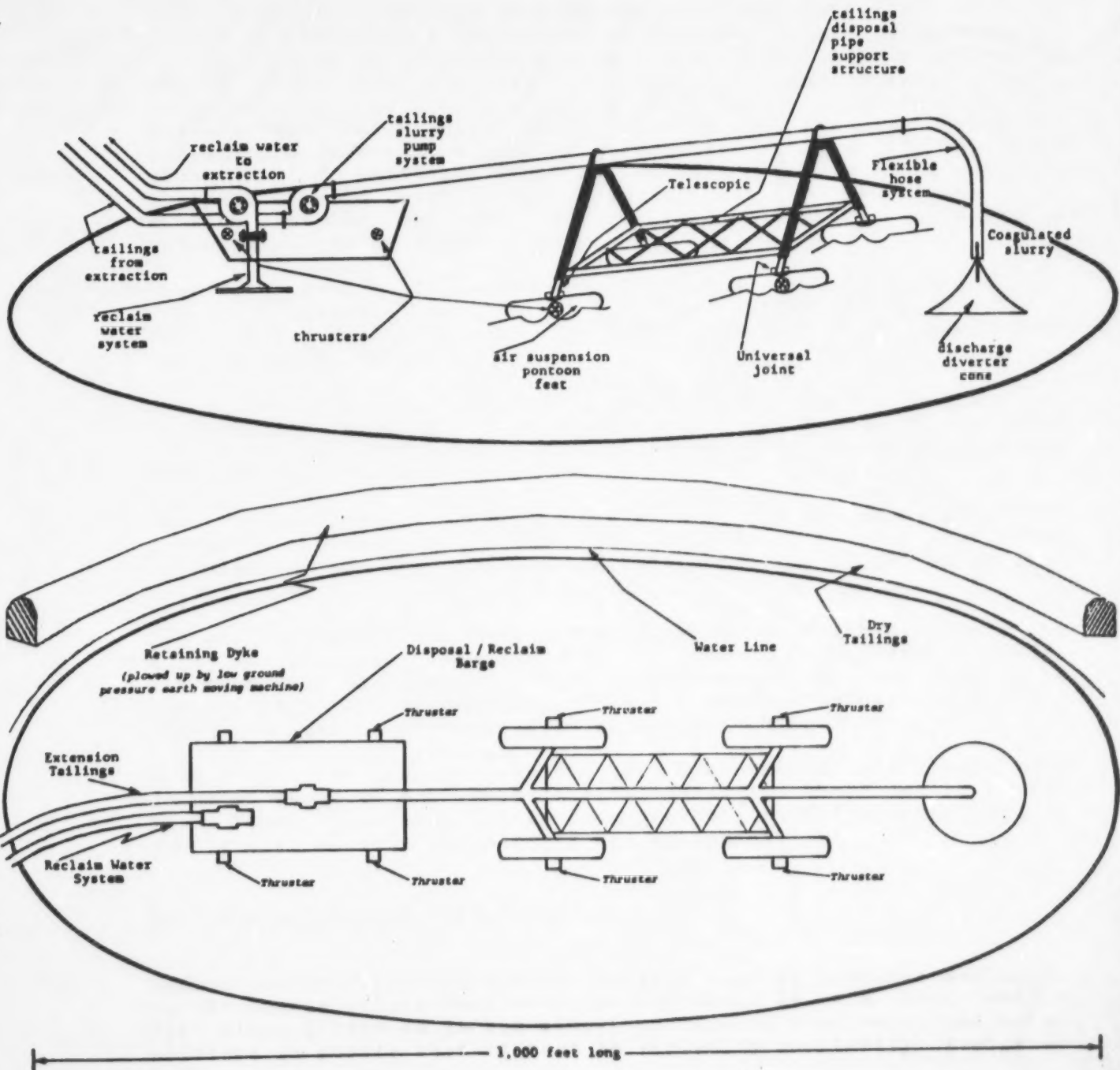
(11.8)



(11.9)

Figure 11.5

"Dry" Tailings Disposal / Water Reclaim Barge



1911

Page 11

The first of the month of January

1911

[Faint, illegible text covering the majority of the page, likely bleed-through from the reverse side.]

12.0 RECLAMATION OF SOIL AND WATER

Reclamation and revegetation of tailings materials is not specifically included in the scope of work for U.P.C.-466. However, parallel work on reclamation of the treated tailings from the chemical treatment process has also been done. This work was funded by the Alberta Environmental Research Trust. A photograph of the testing of jack pine growth characteristics is presented as Figure 12.1. The work in U.P.C.-466 makes use of several basic assumptions on the nature and economics of reclamation of our treated material, which are evaluated in the work funded by A.E.R.T. Because reclamation significantly affects the ultimate economics of tailings disposal, we have assessed costs assuming that our treated tailings soil material can be reclaimed in a similar fashion to the way dyke sand material is reclaimed in existing oil sands operations.

Gary Grant of G.A. Grant and Associates and Jim Sherstabetoff of J.S. Environmental Enterprises Ltd. have worked with C-H Synfuels on the A.E.R.T. funded work. The results of this work have been very encouraging.

The reader of this report who is interested in the reclamation and revegetation aspects is advised to request a copy of the final report on the A.E.R.T. project. It should be available shortly after the report for U.P.C.-466.

The reclamation of tailings wastes from the oil sands plants is currently a three part problem: The reclamation of the sand, the reclamation of the sludge, and detoxification of the associated water.

The reclamation of the sand dykes is well understood. There is also considerable literature on the subject (e.g. Rowell, 1982). For those not familiar with this aspect it is discussed briefly in section 12.1, and estimates based on this technology (E.R.C.B., 1984) are used in the economics in section 13.0.

Some of the known aspects of reclamation of sludge and detoxification of pond water are discussed in sections 12.2 and 12.3. Both of these areas can probably be fairly described as poorly defined both technically and economically.

12.1 Reclamation of Sand Dykes

Hydraulically deposited coarse tailings sand is somewhat analogous to the coarse silica sand used for ashtrays. It is a poor medium for plant growth as it has almost no natural nutrients, and holds moisture so poorly that it must be virtually constantly irrigated

(12.2)

to provide sufficient moisture for vegetation. Proper reclamation by vegetation requires that these and several other soil properties be significantly altered.

The ideal soil for reclamation by vegetation has a number of important physical, chemical and microbial characteristics. The reader can refer to such literature as the "Pit Slope Manual," Volume 10-1 (Canmet, 1977) for a discussion of these properties, which are significant to tailings revegetation.

12.1.1 Physical Characteristics: Particle Size Distribution

An ideal soil for vegetative growth has a wide distribution of particle sizes containing clay, silt, sand and gravel. The clays and to a lesser extent the finer silts provide absorption and cation exchange capacity for nutrients and moisture, the sand provides porosity for movement of moisture and the gravel improves aeration of the soil.

While "whole" oil sands in situ occasionally shows pockets of glacial till gravel, it could not generally be considered to meet this criteria. Aside from the bitumen, it is fairly close to the definition of a sandy soil: 70% sand, 20% silt and 10% clay, which although not ideal for vegetative growth, is workable.

As apparent from Figure 4.1, the coarse sand placed in tailings dykes during hydraulic construction has almost no clay (<1%) and is deficient in silt as well. Normal reclamation procedure for tailings dykes typically involves admixing such finer materials back into the soil.

The reader may observe that the current tailings disposal practise, involving segregation of the sand and clay during dyke and pond construction, actually creates two problems - sludge wetness and sand dryness. Thus our chemical treatment technique, by maintaining the two fractions together should be a significant improvement from either of these extremes.

A properly sized soil with adequate porosity is able to retain sufficient moisture (even above the water table) that "plant available moisture" is within reasonable limits. On the high moisture side, the "field capacity" might be as high as 20%. On the low side the plant "wilting point" might be as low as 6% moisture.

In addition to the actual demands of the plant itself, moisture is critical in the role of transporting nutrients to the vegetation.

12.1.2 Chemical Parameters

Among the chemical parameters important to plant growth are: cation exchange capacity, pH, nutrient levels and levels of organic matter.

12.1.2.1 Cation Exchange Capacity (C.E.C.)

Typical cation exchange capacities for a sandy soil might be 6 meq/100 g. This parameter has been measured for our material in the A.E.R.T. work, and is in approximately the same range. The C.E.C. oil sands tailings of about 5 meq/100 g relates reasonably well to the total known C.E.C.'s of the major clay species present, kaolinite and illite.

12.1.2.2 pH Level

Although tailings materials treated with lime show pH levels of 8 to 10 immediately after treatment which are too high for proper plant growth, (i.e. versus a pH of 5 to 7 for average natural soils) CO_2 from the air reacting with free Ca^{++} and OH^- to form CaCO_3 and HCO_3^- should fairly quickly correct the excess pH problem. Coupled with some degree of natural leaching by precipitation, this characteristic is anticipated to be self correcting.

12.1.2.3 Nutrient Levels

Although a number of macro nutrients such as N, P, K, Ca^{++} and Mg^{++} are known to be important to all forms of plant growth, the nutrient demands of various plant species can be very different. Along with the known particular micro-nutrient demands for a host of substances for various plant species, the question of availability of various nutrients under field conditions is important. Although chemical analysis can show the potential for a nutrient deficiency, it is usually simplest to conduct vegetation growth trials to determine soil suitability (as we have done in the A.E.R.T. research program).

12.1.2.4 Organic Matter

Surficial soils ideally contain up to 5% organic matter. It is believed that bitumen residues might act as poisons for plant species at levels of even 1 to 2%. Many plant species are,

(12.4)

however, able to thrive at well below the 5% organic matter level. Growth and decay cycles usually increase the organic content with time, so even a low level may also be rectified by nature over time.

Based on the low assumed levels of organic matter (other than bitumen) in oil sand tailings, it might be assumed that, as a minimum, peat moss would be required as a soil amendment to improve this characteristic.

12.1.3 Microbial Characteristics

Over time, a healthy soil develops a microbial profile, in the upper 6 inches or so of soil, such as indicated in Table 12.1. These microbes help decompose decaying plant matter and recycle major nutrients such as C, N and P to young plants.

While oil sand tailings are not likely to exhibit much microbial activity, addition of peat moss to surficial material should help develop the microbial population. As for organic matter, the microbial compatibility of various plants are quite different, and best determined by vegetation testing.

12.1.4 Current Experience

Native soils in the Athabasca area typically have a very high organic content and in fact are described as a "humus muskeg" or "peat moss". Because muskeg holds moisture and nutrients extremely well, it is an excellent medium to support growth. But its bearing strength is so low it may be closer to a slurry than a soil in physical properties and be unable to physically support trees or animals and too wet for best plant growth.

The reader will no doubt be aware that muskeg or peat moss as a soil modifier is such an ideal growth medium for plants that peat "mines" have been developed in a number of northern locations in Canada to supply gardens around the world. Its wide availability in the Athabasca area clearly points to its use as an additive to tailings dyke sand at the existing operations or whole tailings to improve moisture and nutrient retention. Through trial and error, the ideal additive mix for tailings dyke sand has been found to be a combination of overburden clay and muskeg. These soil amendment materials, along with fertilizers, are applied mechanically to dyke slopes in existing operations.

At a cost of at least \$10,000 per hectare, it is an expensive process, particularly when it was realized that there may be 5,000 hectares or more requiring this type of reclamation in an oil

sands operation.

Reclamation by vegetation is essential for tailings dykes because wind and water erosion are serious hazards to the integrity of the tailings dykes. The sludge material contained in the dykes is permanently liquefiable and must be impounded in perpetuity in a safe structure. Hence, the reclamation and revegetation of tailings dykes is far from simply an aesthetic improvement in tailings disposal operations.

Although it is theoretically possible to devise methods to dewater, reclaim and revegetate the oil sands tailings ponds sludge, so far there has been no economically attractive technique to accomplish it. When viewed in the context of the properties of the oil sands and the optimum soil properties required for a trafficable, revegetated soil, the reclamation potential presented by whole tailings treatment may be more apparent.

While the regulatory authorities concerned might wish it were otherwise, with current technology the existing operations have no certainty of being able to reclaim the large sludge ponds when the reserves have been exhausted and the plants shut down. While the average person would probably not like to have such a sludge pond in his backyard, in fairness it must be pointed out that such ponds probably don't seem all that different to some people than the natural sloughs in the Athabasca area. One significant difference, however, is that the water associated with this sludge is highly toxic to fish and other plant and animal species.

12.2 Pond Water Quality and Detoxification

Syncrude has committed itself to either detoxify the pond and leave it as a "natural" water body, or to detoxify and drain the tailings pond to surface waters. C-H Synfuels and Zenon have recently begun work investigating the characteristics and methods of detoxification of oil sands tailings pond water (U.P.C. - 526). The methods appropriate for detoxifying existing tailings pond water might also prove to be appropriate for water from the whole tailings treatment technique, but there would be much less water accumulated with whole tailings treatment.

A number of references in the literature (e.g., MacKinnon, 1981), indicated high toxicity levels, such as to rainbow trout of a 96 hour LC_{50} of about 4%. Similarly high levels of toxicity have been measured by other bioassay procedures, such as microtox and Ames tests. Published information and our own work in the area have confirmed that dissolved polar organic constituents are probably responsible for this toxicity.

Table 12.2 summarizes the results of carbon absorption and

(12.6)

acidification tests on both whole tailings, untreated, and the effluent from our treated material. At this point, we believe it is appropriate to consider the toxicity of the effluent from our treatment technique to be comparable to the existing tailings pond water, although it may be less due to lower organic levels.

Because less water is accumulated and current water balance information does not suggest that a bleed stream will be required, ultimate detoxification of water from whole tailings treatment should be considerably less expensive. There are at least three treatment techniques which should be able to accomplish the required detoxification. These are: Acidification, carbon absorption and anion exchange.

12.3.1 Acidification

Reducing the pH of pond water to approximately 2.5 by adding hydrochloric or sulfuric acid has been shown by Syncrude to result in the removal of all toxic organics. Before the water can be discharged to surface it must be neutralized again with caustic. Because of the volume of water involved and the requirement to add both acid and base to produce neutral pH, detoxification by this method is probably expensive. If done on an annual basis to control accumulation it might cost as much as \$40,000,000.00.

12.3.2 Carbon Adsorption

Table 12.3 presents the results of microtox analyses of effluents from our tailings treatment which have been passed through a carbon absorption process. Based on the results of these tests, the current estimate of the cost of tailings water detoxification by this method is approximately \$18,000,000 per year. For the existing operations, it could be expected that a larger treatment process would be implemented for several years following the completion of plant operations, rather than treatment and discharge annually. A lump sum estimate of treatment following termination of the operation is used in Section 13.0..

12.3.3 Anion Exchange

Based on our knowledge of the characteristics of the toxic organic constituents of tailings pond water, namely that they are organic acid type constituents, we expect that an anion exchange process could be used to remove them from a bleedstream. Use of a regenerable anion exchange resin to extract organic acids from tailings pond water has a number of advantages, particularly in

(12.7)

costs. Though we have not identified specific resins and hence do not know at this point precisely how much this approach will cost, we can be virtually certain that it would be significantly less than the \$18,000,000 per year we have estimated for carbon absorption.

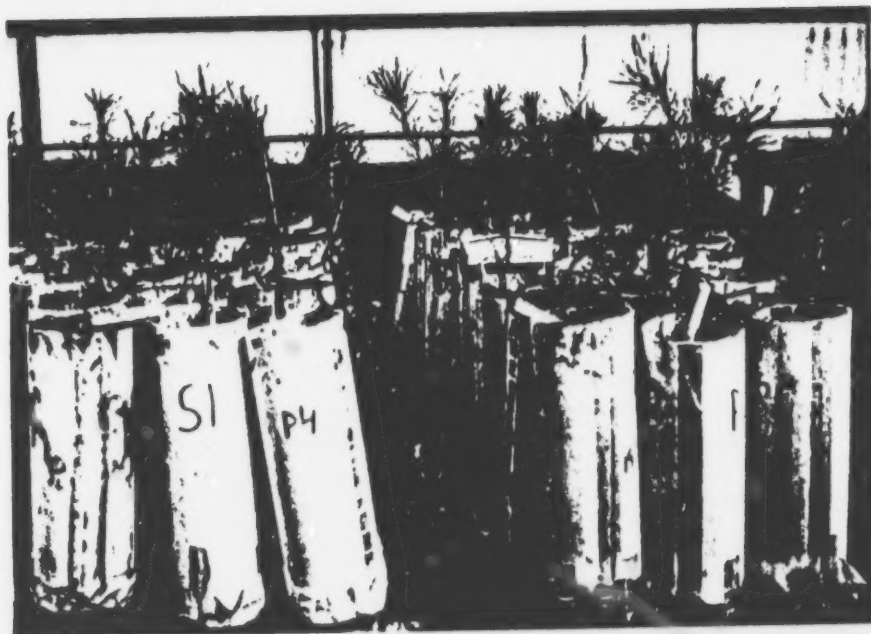
A further advantage of the anion exchange process to removal of toxic organics from a bleedstream to be discharged is that when the anion exchange resin is regenerated, a potentially useful byproduct will probably be generated. Organic acids have in the past been described as beneficial to the extraction process and we would expect that the organic fraction can be returned to the recycle water stream.

All assumptions regarding anion exchange resins remain to be verified, and hence we have used the cost of the carbon absorption process as our base line for complete tailings treatment technology. The potential improvement in the water detoxification should an anion exchange process be proven and applied in practise are an order of magnitude.

(12.8)

Figure 12.1

Jack Pine Reclamation Test Program



(12.9)

TABLE 12.1

<u>Organism</u>	<u>Organisms / gm d.w. of Soil</u>
Bacteria	$10^5 - 10^7$
Fungi	$10^2 - 10^4$
Actinomycetes	$10^1 - 10^2$
Algae	10^2



13.0 DRY DISPOSAL ECONOMICS

Analysis of the economics of an entire oil sand plant would tend to make the distinctions between oil sands tailings disposal options appear insignificant. Many of the economic complexities of an oil sand mining venture, such as royalty payments, are not relevant to tailings disposal. Coupled with the problems of estimating the costs and economics of commercial operations from laboratory scale data, the reader can appreciate the inherent difficulty of making an accurate economic assessment.

This work was undertaken more with the primary objective of identifying the critical areas for process economics than with the intention of developing a definitive comparison of conventional and dry tailings disposal.

13.1 Tailings Disposal Cash Flow Analysis

One way to address only the tailings disposal part of an oil sand plant, yet retain the correct overall economic implications, is to calculate the impact on total project cash flow of the tailings disposal portion of the plant. In this case, the annual capital and operating cost, tax write offs and other considerations are all treated the same as though the entire plant was being analyzed and "flow thru" overall taxation status assumed. These terms are explained more fully in the subsequent discussion. The resultant interpretation of tailings disposal economics proves, as will be seen later, to be relatively stright forward.

As with typical oil sands plant economics, the most crucial factors for the analysis are the so called "global variables" such as inflation, but at least oil pricing as one difficult global variable can be ignored. (Incremental oil recovery can be conducted as part of a tailings disposal operation, but for most purposes, the various "add-on" tailings oil recovery operations can be considered independently of the tailings management options.)

Major economic factors for the tailings disposal operations are annual capital investment costs, as adjusted for differences in the write off treatment and operating costs. Both capital and operating cost expenditures are assumed to rise at the same annual rate of inflation, which although an independent variable, is currently assumed to be 5% over the life of the project. In all cases where assumptions are significant, the impact on project cash flows are estimated via sensitivity studies, described later in the section.

In the discussion which follows, the capital equipment items for conventional tailings disposal and dry tailings are discussed, following the order of the computerized economic analysis models presented in Tables 13.1 and 13.2. For an excellent conventional

(13.2)

tailings disposal cost data base, the reader should review a recent E.R.C.B. report, (E.R.C.B., 1984). This report forms the primary basis for capital and operating costs used here.

13.2 Capital Equipment; Conventional Disposal

13.2.1 Heavy Equipment (Example)

The equipment such as bulldozers needed for conventional tailings disposal is usually estimated by the volume of material that must be handled in a given period of time, usually on an annual basis. For conventional tailings disposal dyke construction operations, the bulldozers are used for plowing up berms to contain the sand which is placed hydraulically. It is then "track packed" by the same wide tracked D-6 type Caterpillar dozers in order to achieve the consolidation required to satisfy geotechnical concerns. Suncor (Great Canadian Oil Sands) originally expected to use "sheep's-foot" rollers for compaction of dyke sand material but in actual operation track packing by dozers proved to be sufficient consolidation of the dyke sand.

The principle equipment required for conventional dyke construction is thus three wide track D-6 dozers per tailings outlet (i.e. 7 active tailings outlets, 1 spare) or 21 machines for both berm construction and tailings compaction during hydraulic placement. Perhaps only two of these dozers might actually be working at any one site at any particular time for hydraulic dyke construction, but it is possible that all 7 tailings outlets might have dyke construction and sand placement going on at the same time.

13.2.2 Topography

One key assumption about tailings disposal operations is that the general area of the tailings dyke is flat (i.e. not the situation Syncrude had where tailings were initially placed in Beaver Creek Valley). A topographical depression complicates the analysis and is likely to be inappropriate for many other operators. For Syncrude, a starter dyke was only required at the north and south ends of Beaver Creek). Dyke construction from then on employed hydraulic placement.

By utilizing the natural topography Syncrude was able to minimize the amount of material placed by "cut and fill" methods which is approximately 10 times as expensive as material placed by "hydraulic" construction (i.e. about \$6.00/m³ versus \$.60/m³). While it is obvious that an operator would seek to take advantage of the natural topography in his vicinity to minimize construction of earth fill starter dykes, it cannot be assumed that every operator would have such natural topography. In any event, topography is not likely to be a significant factor in discriminating between conventional and dry disposal options. The

(13.3)

case assumed is that of minimal advantage from natural topography, (as occurred in Alsands case).

13.2.3 Earth Fill Starter Dykes

The amount of earth fill required for starter dykes for conventional tailings disposal is estimated by first calculating the surface (settling) area that will ultimately be required for the pond and then the dyke corresponding volume. From this, the dyke volume can be calculated and from that the volume of starter dyke required for construction (within satisfactory safety limits). The volume of earth fill starter dam is then multiplied by the unit volume cost factor to estimate the total cost for the earth fill dam construction contract. This would usually be handled by a separate contractor (not the plant operator), as it is a temporary requirement.

13.2.4 Tailings Lines and Pumps

The other major portion of the capital equipment required, is tailings line. Because of the size of the lines needed (20 inches) the extent (up to 13 kilometers each) and the number (8), approximately 67 kilometers of tailings line is needed from the initial start up. Experience has shown that this tailings line, due to very high erosive wear and damage due to frequent movements by heavy equipment, has to be replaced frequently. As well, because tailings disposal operations in the mined out area gradually move away from processing operations, additional tailings line is required over the years.

13.2.5 Equipment Service Life (Replacement Intervals)

Only slightly more than a 2 year service life is obtained on typical 20 inch line in commercial service, so that the entire tailings line would need to be replaced approximately every 2 years.

Heavy equipment, such as bulldozers, in oil sands operations, lasts about 5 years (with the exception of less intensively used support equipment such as motor graders which might last 8 years) so that virtually the entire heavy equipment fleet must be replaced every 5 years. In practice, the equipment lives would be staggered such that a relatively uniform amount of tailings line and heavy equipment would be replaced every year.

13.2.6 Dry Disposal; Capital Equipment

Equipment requirements for dry disposal can be estimated in much the same fashion as they are estimated for conventional disposal, based on volume or weight of material that must be handled. As we have estimated the out of pit volume required for dry disposal as approximately 75% of that required for conventional tailings

(13.4)

disposal, we can reasonably forecast that the equipment requirement for dry disposal would be no more than 75% of that required for conventional disposal. (This estimate assumes that proportionately less equipment is needed in dry disposal than in conventional tailings dyke construction operations because overbording always occurs at the same locations, greatly reducing the labor and equipment intensive pipe movement operations. The 75% estimate is deemed as very conservative in the light of this aspect.)

One major distinction between the dry tailings disposal option and conventional disposal is that by chemical treatment we are able, as discussed in section 8, to transport tailings slurry at about 50% of the velocity of conventional tailings pumping. It has been estimated that the combined result of the reduction in erosion and abrasion in tailings pipe and the greatly reduced requirement for pipe movement to be a more than doubling of the tailings pipe service life (i.e. from 2 to 4 years).

While this conclusion must obviously be proven under actual field conditions, it seems more than feasible from the expected reduction in the pumping velocity. With the lime treatment process it is estimated to be roughly 50% of that required for conventional tailings disposal operations. (As abrasion is usually a third order function of the slurry velocity, the assumption of at least a 50% reduction of abrasion and a doubling of the service life is conservative.)

It is apparent that with in excess of \$10 million/year for tailings pipe the cost saving is significant over the life of the project.

13.3 Tax Write Offs

There are four tax write off categories that are significant to the investment requirements for the tailings disposal operations of an oil sands plant. These four are: the Investment Tax Credit (I.T.C., a 10% "grant"), Class 28 depreciation (CL28, a 30% declining balance write-off), so called Canadian Exploration Expense C.E.E., or "Pre-Production" a 100% write off), and Supplemental Depletion (a 1/3 investment cost not subject to an investment tax credit deduction, as are the other two categories).

The tax considerations involved in an oil sands project must be evaluated, even when considering just tailings disposal operations, if the cost is to be accurately determined. For example, as was the case for the oil exploration operations in the Beaufort Sea at one point, the actual cost to a Canadian corporation paying income tax at 50%, of an investment with a 200% write off was \$0. Hence, the cost to a company of the investment, while not usually affected this much, may be much less when considered after tax.

Allowing for the flow through of write offs to the investing company is important in the evaluation of oil sands operations where tax considerations are significant and change from time to time. They are the main reason why oil sands plants are usually "flow through" joint ventures.

13.3.1 Company Taxation Status

In considering the impact on an owner company of an oil sands facility it is necessary to distinguish between taxable Canadian corporations, non taxable corporations, taxable foreign corporations, and non taxable foreign corporations. The latter case can also be referred to as "separate project" economics, as it is identical to a new or separate project for a new company (not paying taxes) just being established.

In the discussion which follows, the owner of an oil sands plant, of which the tailings disposal facilities described form a part, is assumed, unless otherwise stated, to be a taxable Canadian corporation. Hence the impact on the company is measured by so called "flow-through" economics which allows the company to use the write offs from oil sands facilities against its income from other sources. (This is the best use of the write offs a company can make.)

A company would normally ensure that its other income is larger than the write offs involved for an oil sands facility investment. If this is the case, the tax impact of investments in oil sands facilities can be considered on a consistent basis, with all of the available write-offs serving to reduce taxes paid on other parts of a company's business.

If, in fact, there was reason to expect that a company's taxable income position might change throughout the life of such a facility, the "flow through" assumption would not be correct. However, for most corporations the tax position will probably not change throughout an oil sands project life.

The Alsands example is indicative of the utility of this assumption. Eight of the nine companies participating in Alsands expected to be able to use all of the write-offs from the project. They also expected that the ninth company, which could not apparently make use of them, would drop out. (The adverse impact on the project economics for a company in this position was at least a 4% reduction in the "discounted cash flow rate of return" D.C.F.R.O.R.)

13.4 Operating Expenses

A detailed operating cost estimate of such components as the staff required for conventional tailings disposal operations is also

(13.6)

presented in the E.R.C.B. study. Those same cost estimates are used here. However, the overall approach to plant economics used in that study is different, as they include depreciation, net income and income tax as components of operating costs. These three components are not included in this analysis.

Operating costs for the dry disposal operation are estimated at 80% of conventional disposal costs, allowing for some economies of scale for a conventional disposal operation over dry disposal. As for capital costs, it is believed that much less activity is required to operate the dry tailings system, but the chemicals consumed do represent an additional cost burden.

80% of conventional disposal costs may also be an understatement of the savings for the dry disposal operating costs because DTD will not require extensive and frequent tailings pipe rotation and other expensive tailings line maintenance. An accurate assessment of the resultant cost savings from such aspects of dry disposal requires a more detailed operating plan and confirmation of estimates from actual experience.

It is realistic to anticipate that the overall economics of the dry disposal process might be even better than those presented here.

13.5 Inflation Factor Adjustment

Both the equipment expenditure estimates and the operating costs used in the economic analysis are based on 1983 values. Expenditures made from 1984 to 2000 or later will be in inflated dollars and an adjustment must be made for both capital investments and operating expenses during subsequent years. For the purposes of the study, a 5% annual inflation factor has been used for both capital and operating costs. However, it is recognized that estimation of future inflation factors is one of the most difficult of economic projections: the program can be readily modified to look at other inflation scenarios, if desired.

13.6 Present Value Comparison of Conventional and Dry Tailings Disposal

A variety of different standards are available to judge the economic merits of a particular project. Oil sands plants are typically analyzed as a whole in terms of the D.C.F.R.O.R. that an investor would see for his share of the project. The rationale for D.C.F. rate of return analysis implies that a company requires a minimum rate of return or "hurdle rate" to decide if the investment is attractive.

Some companies also use a "present value" (PV) calculation which

discounts dollars spent or earned in future back to a current value. The discounting factor might, in fact, be the same as the rate of return that the company expects. (With a PV analysis, as long as the time discounted revenues less expenditures for the project are positive then the project would be attractive.)

A major advantage of the PV concept over a rate of return analysis is that the present value method can be used when all the project cash flows are either completely positive or completely negative e.g. when a project yields only revenue, or when a project is only an expenditure. Tailings disposal operations, although an integral part of an oil sands plant, do not contribute any revenue, unless oil or minerals reprocessing is included. Oil or minerals recovery could be done in conjunction with tailings disposal operations, but there is no direct connection between them.

Table 13.3 presents a present value comparison at 0, 5, 10, 15 and 20% present value factors for conventional and dry disposal economic cases. Significantly, the dry disposal option is about 20% cheaper than conventional disposal for all the present value factors considered. This is probably due to the fact both the capital and the operating costs for dry disposal are cheaper than for conventional disposal.

13.7 Sensitivity Studies

One of the simplest methods to estimate the validity of the assumptions used in the economic analysis is to do sensitivity studies. The relatively straight forward nature of the "flow-through" analysis makes it possible to estimate the overall cost impact to a participating company in an oil sand project of any changes in capital and operating costs. Changes in "global" factors such as inflation, (unless they affect capital and operating costs differently) do not affect the relative costs of conventional and dry tailings disposal.

The sensitivities indicate that capital would have to be about 150% higher than our most realistic estimate or operating costs about 35-40% higher for dry disposal to be as costly as conventional tailings disposal.

Due to the attractive investment write-offs available to oil sands developers it is obvious that capital expenditures for tailings disposal are not of as much concern (per dollar) as operating expenditures (i.e. in other words, capital expenditures are paid for with so-called \$.25 dollars). This is generally true for oil sand operators and accounts for why they generally prefer to buy equipment, even for seasonal operations, to do work themselves (such as tailings disposal, muskeg and overburden removal) rather than subcontract to other operators.

Obviously, a process developer hoping to introduce a concept to oil sands developers, at least within the existing fiscal regime, must be more concerned about operating cost estimates than for capital. Unfortunately, the nature of operating cost estimates (which require considerable operations familiarity with the technology) are considerably more difficult to make accurately than capital cost estimates, especially for a novel technology. In the present instance, a great deal more information and conceptual design analysis will be required before definitive economics can be established.

At capital expenditures of about 150% above those currently indicated for dry disposal, the dry disposal case may be superior to some but not all of the present value cases for conventional disposal. Also, for operating expenses of 37% above those estimated for the dry disposal case, conventional disposal might be cheaper than dry disposal for some of the present value rates.

An alternative view of these sensitivities on capital and operating expenses is that they are "contingency" allowances for higher capital or operating expenses that dry tailings disposal could tolerate and still be a preferred option to conventional tailings disposal.

13.8 Potential Cost Reductions

Some analyses have been made of further potential cost reductions that might be achieved with the chemical treatment technique. A good example of such a possibility is the potential for production of lime in the Fort McMurray area by calcination of McMurray formation limestone with byproduct coke.

Improved reclamation procedures, alternative central discharge layouts which allow more hydraulic construction and several equipment options also appear to offer excellent potential for cost reductions over our current conceptual dry tailings base case.

While these opportunities for further cost reduction are very intriguing, it is believed that the development efforts at this point are better spent on developing improved confidence in the workability of the "base case."

13.9 "External" Economic Cost Factors

It should be remembered that throughout this economic analysis no provision has been made for the cost of reclamation of sludge from the tailings pond in the conventional disposal case. One approach which has been suggested is to bulldoze vast quantities of dry sand into the sludge at the bottom of the tailings pond. For the quantity of sand required this would be an extremely expensive

chore. It is not clear whether this will really be required or whether it is anywhere near economically practical for existing operations.

While Suncor and Syncrude are attempting small scale trials for sludge oil recovery and reprocessing, cost estimates for large scale reclamation of sludge are very difficult to make. It should also be noted that virtually all of the current industry work on the sludge problem regards oil recovery from sludge reprocessing as a critical element to the economics of this strategy. As tailings oil recovery operations are implemented at both Syncrude and Suncor as a part of plant operations, economic recovery of oil from sludge will become increasingly more difficult.

In the case of chemical treatment of tailings, we could also recover the oil prior to solids placement in a tailings area so that oil recovery is not an intrinsic advantage to the concept of sludge reprocessing. It is also believed that dry disposal technology has the capability to reprocess some sludge and entrain it with whole tailings for disposal.

A preliminary economic evaluation suggests it may be preferable to alternatives which require complete reprocessing of the sludge at the termination of the project. A definitive economic comparison would require specific information about the amounts, the nature and timing of sludge being reprocessed and entrained in whole oil sands tailings for disposal.

If the required information were available from project operators, the program can be readily modified to analyze the comparative economics of such sludge treatment techniques currently being proposed and evaluated.

Table 13.1

Conventional Disposal Economics

YEAR	RECLAMATION REVENUE	CAPITAL EXPENSE	INVEST TAX CREDIT	PREPRODUCT EXPENSE	CLASS 28 (CCA)	OPERATING EXPENSE	INFLATION FACTOR	AFTER TAX CASHFLOW
1985	\$0.00	\$15000.00	\$1500.00	\$13500.00	\$0.00	\$21000.00	1.05	(\$29137.50)
1986	\$0.00	\$38000.00	\$3800.00	\$34200.00	\$0.00	\$26000.00	1.10	(\$47517.75)
1987	\$0.00	\$50000.00	\$5000.00	\$25200.00	\$5940.00	\$26000.00	1.16	(\$64167.15)
1988	\$0.00	\$6700.00	\$670.00	\$70.00	\$5967.00	\$26000.00	1.22	(\$35306.20)
1989	\$0.00	\$700.00	\$1670.00	\$70.00	\$4365.90	\$26000.00	1.28	(\$31201.32)
1990	\$0.00	\$700.00	\$70.00	\$70.00	\$7565.13	\$26000.00	1.34	(\$49915.13)
1991	\$0.00	\$700.00	\$670.00	\$670.00	\$5484.59	\$26000.00	1.41	(\$33612.40)
1992	\$0.00	\$23100.00	\$2310.00	\$2310.00	\$5648.21	\$26000.00	1.48	(\$43150.41)
1993	\$0.00	\$700.00	\$70.00	\$70.00	\$10190.75	\$26000.00	1.55	(\$64682.05)
1994	\$0.00	\$700.00	\$700.00	\$700.00	\$7322.52	\$26000.00	1.63	(\$37413.65)
1995	\$0.00	\$27000.00	\$2700.00	\$2700.00	\$5314.77	\$26000.00	1.71	(\$41001.31)
1996	\$0.00	\$700.00	\$700.00	\$700.00	\$11010.34	\$26000.00	1.80	(\$80445.08)
1997	\$0.00	\$700.00	\$700.00	\$700.00	\$9597.24	\$26000.00	1.89	(\$51857.96)
1998	\$0.00	\$11000.00	\$1100.00	\$1100.00	\$8608.07	\$26000.00	1.98	(\$55430.10)
1999	\$0.00	\$1000.00	\$100.00	\$100.00	\$8995.65	\$26000.00	2.08	(\$65282.87)
2000	\$0.00	\$1000.00	\$100.00	\$100.00	\$6566.95	\$26000.00	2.18	(\$51551.91)
2001	\$0.00	\$20000.00	\$2000.00	\$2000.00	\$4866.87	\$26000.00	2.29	(\$56077.82)
2002	\$0.00	\$7000.00	\$700.00	\$700.00	\$8806.81	\$26000.00	2.41	(\$95293.93)
2003	\$0.00	\$1000.00	\$100.00	\$100.00	\$8054.76	\$26000.00	2.53	(\$71443.50)
2004	\$0.00	\$17000.00	\$1700.00	\$1700.00	\$5908.34	\$26000.00	2.65	(\$63535.42)
2005	\$0.00	\$1000.00	\$100.00	\$100.00	\$8725.83	\$26000.00	2.79	(\$102905.33)
2006	\$0.00	\$27000.00	\$2700.00	\$2700.00	\$6378.08	\$26000.00	2.93	(\$69360.73)
2007	\$0.00	\$1000.00	\$100.00	\$100.00	\$6354.66	\$26000.00	3.07	(\$89450.97)
2008	\$0.00	\$1000.00	\$100.00	\$100.00	\$11738.26	\$26000.00	3.23	(\$143293.99)
2009	\$0.00	\$1000.00	\$100.00	\$100.00	\$8486.78	\$26000.00	3.39	(\$76723.32)
2010	\$0.00	\$24000.00	\$2400.00	\$2400.00	\$6210.75	\$26000.00	3.56	(\$84605.90)
2011	\$0.00	\$7000.00	\$700.00	\$700.00	\$10827.52	\$26000.00	3.73	(\$157500.48)
2012	\$0.00	\$7000.00	\$700.00	\$700.00	\$9469.27	\$26000.00	3.92	(\$108059.80)
2013	\$0.00	\$50000.00	\$5000.00	\$5000.00	\$8518.49	\$26000.00	4.12	(\$115419.56)
2014	\$0.00	\$383000.00	\$38300.00	\$38300.00	\$20962.94	\$35000.00	4.32	(\$322064.79)
TOTAL	\$0.00	\$210309.00	\$21030.90	\$21030.90	\$227886.47	\$784000.00		(\$2337408.33)
NPVU5	\$0.00	\$142996.44	\$14299.64	\$14299.64	\$102609.15	\$397004.22		(\$983306.76)
NPV10	\$0.00	\$110087.41	\$11008.74	\$11008.74	\$55245.87	\$241070.10		(\$517080.15)
NPV15	\$0.00	\$90719.61	\$9071.96	\$9071.96	\$33996.41	\$166503.57		(\$325051.94)
NPV20	\$0.00				\$22977.84	\$125323.59		(\$231352.38)

(13.10)

Table 13.2

Dry Tailings Disposal Economics

(13.11)

YEAR	RECLAMATION REVENUE	CAPITAL EXPENSE	INVEST TAX CREDIT	PREPRODUCT EXPENSE	CLASS 28 (CCA)	OPERATING EXPENSE	INFLATION FACTOR	AFTER TAX CASHFLOW
1985	\$0.00	\$11000.00	\$1100.00	\$9900.00	\$0.00	\$17000.00	1.05	(\$23047.50)
1986	\$0.00	\$29000.00	\$2900.00	\$26100.00	\$0.00	\$21000.00	1.10	(\$37540.13)
1987	\$0.00	\$38000.00	\$3800.00	\$25200.00	\$2700.00	\$21000.00	1.16	(\$47752.03)
1988	\$0.00	\$50000.00	\$500.00		\$3240.00	\$21000.00	1.22	(\$29026.29)
1989	\$0.00	\$500.00	\$50.00		\$2403.00	\$21000.00	1.28	(\$25842.79)
1990	\$0.00	\$13500.00	\$1350.00		\$5327.10	\$21000.00	1.34	(\$40854.76)
1991	\$0.00	\$500.00	\$50.00		\$3863.97	\$21000.00	1.41	(\$27463.81)
1992	\$0.00	\$5000.00	\$500.00		\$4054.78	\$21000.00	1.48	(\$34679.74)
1993	\$0.00	\$5000.00	\$500.00		\$4188.35	\$21000.00	1.55	(\$36310.12)
1994	\$0.00	\$17500.00	\$1750.00		\$7656.84	\$21000.00	1.63	(\$53625.78)
1995	\$0.00	\$500.00	\$50.00		\$5494.79	\$21000.00	1.71	(\$31987.80)
1996	\$0.00	\$20500.00	\$2050.00		\$9381.35	\$21000.00	1.80	(\$62422.75)
1997	\$0.00	\$5000.00	\$500.00		\$7916.95	\$21000.00	1.89	(\$40619.76)
1998	\$0.00	\$5000.00	\$500.00		\$6891.86	\$21000.00	1.98	(\$43665.55)
1999	\$0.00	\$0500.00	\$850.00		\$7119.30	\$21000.00	2.08	(\$52161.03)
2000	\$0.00	\$750.00	\$75.00		\$5186.01	\$21000.00	2.18	(\$41653.60)
2001	\$0.00	\$750.00	\$75.00		\$3832.71	\$21000.00	2.29	(\$45287.18)
2002	\$0.00	\$15000.00	\$1500.00		\$6732.90	\$21000.00	2.41	(\$74926.60)
2003	\$0.00	\$5000.00	\$500.00		\$6063.03	\$21000.00	2.53	(\$56776.75)
2004	\$0.00	\$750.00	\$75.00		\$4446.62	\$21000.00	2.65	(\$51611.13)
2005	\$0.00	\$13000.00	\$1300.00		\$6622.63	\$21000.00	2.79	(\$81875.77)
2006	\$0.00	\$750.00	\$75.00		\$4838.34	\$21000.00	2.93	(\$56328.32)
2007	\$0.00	\$5000.00	\$500.00		\$4736.84	\$21000.00	3.07	(\$71049.20)
2008	\$0.00	\$21500.00	\$2050.00		\$8850.79	\$21000.00	3.23	(\$112957.85)
2009	\$0.00	\$750.00	\$75.00		\$6398.05	\$21000.00	3.39	(\$62566.21)
2010	\$0.00	\$750.00	\$75.00		\$4681.14	\$21000.00	3.56	(\$68746.91)
2011	\$0.00	\$18000.00	\$1800.00		\$8136.80	\$21000.00	3.73	(\$123695.39)
2012	\$0.00	\$5000.00	\$500.00		\$7045.76	\$21000.00	3.92	(\$86153.15)
2013	\$15000.00	\$5000.00	\$500.00		\$6282.03	\$21000.00	4.12	(\$30290.58)
2014	\$15000.00	\$4000.00	\$400.00		\$16397.42	\$28000.00	4.32	(\$193628.59)
TOTAL	\$30000.00	\$291500.00		\$61200.00	\$170489.35	\$633000.00		(\$1744547.06)
NPV05	\$7114.86	\$291500.00		\$54870.75	\$75028.68	\$320631.59		(\$757105.32)
NPV10	\$1805.22	\$101712.84		\$49503.38	\$39166.12	\$194730.00		(\$405786.56)
NPV15	\$487.07	\$81413.59		\$44913.45	\$23286.51	\$134513.03		(\$257235.60)
NPV20	\$139.02	\$6115.27		\$40958.33	\$15212.12	\$101253.82		(\$183466.86)

(13.12)

TABLE 13.3

PRESENT VALUE COMPARISON OF CONVENTIONAL
AND DRY DISPOSAL ECONOMICS
(\$ BILLION)

Present Value Factor	Conventional Expenditure	"Dry" Disposal Expenditure	Per Cent Differential " " (on Conventional Expense)
PV 50 (ie. Total)	2.34	1.74	26
PV 5	.98	.76	22
PV 10	.51	.41	20
PV 15	.32	.26	19
PV 20	.23	.18	22

14.0 CONCLUSIONS

14.1 Treatment Conditions

14.1.1 Lime Levels

Levels of lime (CaO) in excess of 900 mg/l are able to coagulate and settle the whole tailings used in these experiments as a relatively homogeneous deposited solids. (900 mg/l lime is equivalent to perhaps 500 ppm weight of lime on a whole tailings basis).

14.1.2 Addition of a Polymeric Coagulant Aid

The solids tend to settle more quickly and form a denser but more permeable settled solids phase if a small amount (8 mg/l) of a polymeric coagulant aid (Cynamid A-110) is added to the lime coagulated system (5 ppm weight on whole tailings).

14.1.3 Key Factors Determining Required Lime Addition Level

The optimum lime addition rate increases proportionally as bicarbonate (HCO_3^-) in the extraction tailings increases. High levels of sulfate in the tailings water could also react with lime to precipitate CaSO_4 . The optimum lime level also depends on the type and amount of clay present. (Illite probably consumes about 3x as much lime as the same weight of kaolinite does.)

14.1.4 The Lime Mixing Time

Optimum mixing time for lime is about 30 minutes, but is not a critical variable. Shorter mixing times also work almost as well, and longer mixing times may be marginally better.

14.1.5 Polymer Mixing Time

The optimum mixing time for polymer is about 30 seconds prior to deposition. Longer mix times are probably acceptable, but may tend to degrade the polymer.

14.2

14.1.6 Problems With Air Entrainment

Excessive mixing in contact with air is to be avoided as it entrains air and contributes to solids segregation (layers in the deposited solids) and dirty (high solids) runoff water. It can of course be avoided by in-line mixing, but is probably also wasted energy. The coagulated slurry is much more easily suspended than untreated tailings.

14.1.7 Pumping Velocity

Chemically coagulated whole tailings, as a "non-segregating" slurry requires much less effort to mix and suspend than untreated tailings. It is estimated that the coagulated slurry can be pumped at half of the velocity required for untreated whole tailings.

14.1.8 Treatment Sensitivity to System Variability

While the material has identifiable optimums for chemical levels, mixing times, mixing rates etc. failure to achieve optimum conditions is not catastrophic.

Insufficient chemicals, mixing time or mixing energy results in some segregation, while excessive lime or polymer is primarily an economic burden. At very high levels of excess lime use, residual Ca^{++} or alkalinity can be problems, but they are easily solved by aeration or carbonation which is relatively inexpensive.

14.1.9 Chemical Addition Control Strategies

Observation of settling behaviour (specifically settled density) on actual deposited material could be used as process control strategy for chemical levels, although pH, on-line clay particle zeta potential, slurry viscosity measurement or several other parameters may be useful as process control methods. It is believed that measurement of excess Ca^{++} by an ion specific electrode may be the preferred chemical addition variable to monitor for a process control strategy.

14.2 Water Treatment

14.2.1 Alkalinity Control

Recycle water alkalinity is probably the most significant water quality concern and can be controlled to maintain a satisfactory extraction process alkalinity by aerating (or carbonating) part of the effluent. It would be desirable to recirculate the recycle water stream at the highest pH level that the process can tolerate to minimize the expense of such treatment.

14.2.2 Use of Excess Lime

Lime dosage rates above the optimum may be desirable to minimize segregation if air entrainment has occurred, but at an economic penalty and with potential ramifications due to excessive alkalinity mentioned in 14.2.1.

14.2.3 Recycle Water Quantity

The chemical treatment process results in faster recycle water availability at greater overall quantities than current disposal technology. The estimated amount of recycle water available is 80% versus about 65% for current disposal and recycle methods.

14.2.4 Recycle Water Quality

A buildup of inorganic process water contaminants such as chloride (due to formation salinity) is viewed as the major potential water quality problem due to the higher levels of recycle water attainable with chemical treatment. This could be controlled by treatment of a bleed stream, if necessary. Currently available data does not suggest a salinity problem even for 30 years of operation at 80% recycle in a Syncrude type situation.

14.2.5 Bleed Water Treatment

The cheapest and most effective salinity control is surface disposal of a treated bleed water stream. The primary treatment required is detoxification by organics removal. A second more expensive strategy for bleed water disposal is treatment of the water to in-situ steam quality and its use at an in-situ steam

14.4

injection project, if one is nearby.

14.3 Geotechnical Properties

14.3.1 Homogeneity of Settled Solids

At lime dosage rates of 1500 ppm on whole tailings or 900 ppm lime and 8 ppm polymer a homogeneous settled solids is obtained in flume testing. (These dosage rates are somewhat lower than those indicated in the coagulation and settling tests and may have been somewhat below the optimum.)

14.3.2 Drainage and Drying Rates

The material deposited in the flume tests continues to drain for about 2 days and air dries to what appears to be a trafficable condition in about one week.

14.3.3 Drainage Equilibrium

Drainage equilibrium is achieved on a 3 Metre column of treated material in about 1 week.

14.3.4 Capillary Moisture Retention

Capillary moisture retention by the clays retained in the whole tailings is about 1 metre. This would result in a tendency of the deposited clay containing whole tailings to hold the water table about 1 metre higher than it would otherwise be due to hydraulic conductivity and surrounding water heads.

14.3.5 Whole Tailings Permeability

Horizontal and vertical permeabilities of the material appear to be comparable and ranged from 1.4×10^{-5} cm/sec to 1.3×10^{-4} cm/sec for various whole tailings samples and treatments tested. This permeability range is comparable to beach material in current disposal systems.

14.3.6 Settled Density

At chemical dosage rates which preclude segregation, high settled solids densities are obtained ($1400 - 1700 \text{ g/cm}^3$); in one case at optimum conditions, the material was hydraulically deposited at essentially the in-situ density of the original oil sand.

14.3.7 Bulking Factor

The bulking factor for disposal of treated whole tailings is well below the range of 1.35 to 1.4 typical of current tailings disposal systems. It is less than 1.1 on a routine basis and a value of 1.00 (yes, 1.00!) was obtained in one test; (i.e. the in-situ density referred to in 14.3.6).

14.3.8 Liquefaction Potential

Properly drained, the material shows very little tendency to reliquify when additional slurry is deposited on its surface. Also, the high deposited solids density and lack of compressibility evidenced in some of the consolidation tests are consistent with a high degree of sand grain contact.

14.3.9 Shear Strength

The measured angle of internal friction, is high and fairly consistent in the range of 31 to 37 degrees, suggesting the treated material has good strength characteristics.

14.3.10 Compaction Characteristics

Lime only treated material tends to form a "fluffier" floc which is more affected by handling than lime plus polymer mixes. It also seems to show a greater tendency to compaction under loading.

In all cases chemically treated whole tailings was compacted to a non-liquefiable density at an applied pressure of 16 tons per square foot, equivalent to the self weight of a 100 foot depth of material.

14.3.11 Soil Stabilization Mechanism

While there is considerable evidence of cohesion and bonding taking place in deposited treated whole tailings, the process appears to be one of carbonation. It has so far proved to be somewhat erratic in behaviour (there are a number of known chemical reactions which may interfere). Although carbonation is nature's method of (ultimately) forming very strongly bonded sandstones and other consolidated sediments, we feel it is most conservative and safest to consider any potential geotechnical property improvement due to particle bonding as a bonus, at least at this stage of the technology development.

14.4 Disposal System Design Characteristics

14.4.1 Central Discharge Configurations

Best use of the "hindered settling" material properties involves designing for the minimum volume of containment dyke. This is achieved most easily by a central discharge configuration which exerts minimal stress on the exterior dykes.

The system may also lend itself to an innovative approach which allows construction of dykes hydraulically but overboards the majority of the material at a central point or in an annular fashion around a central point.

14.4.2 Dyke Construction Cycle

Based on what appears to be about one week of drainage/drying to achieve trafficability on hydraulically deposited material, construction of dykes from the material seems straight forward-but should obviously allow for at least a one week delay. Otherwise, no major changes in hydraulic dyke construction methods or equipment appear to be essential. Under certain circumstances it might be desirable to further compact the material with a "sheep's foot" roller or a vibratory compactor.

14.4.3 Lime Addition System

A variety of methods of adding lime are potentially attractive but to allow maximum residence time for mixing, addition of lime at the extraction tailings pumphouse is preferred. It may prove feasible to inject a lime slurry directly into the pump casing to

take advantage of mixing energy provided by the pump. A more conventional method would be in-line mixing immediately ahead of extraction pumping, if possible.

14.4.4 Tailings Pumping and Pipelining

In the coagulated condition, whole tailings should be capable of being pumped at much lower velocities (estimated at 50% of that currently required). This should result in greatly reduced pipeline erosive wear (wear is proportional to V^3) and maintenance. It could also permit pumping of tailings over much greater distances to remote disposal sites and/or (potentially) operation of extraction at higher solids concentrations.

14.4.5 In Pit Disposal

Earlier in pit disposal should be possible with treated tailings based primarily on a reduced concern for a liquefaction hazard with the material.

14.5 Process Economics

14.5.1 Dyke Volumes

Based on the requirement to impound less material out of pit as a result of reduced bulking factors and the resultant lower dyke volumes from the central discharge approach, capital and operating costs lower than conventional disposal systems seem indicated by conceptual design studies to date. A precise cost comparison requires a site specific design.

14.5.2 Capital Cost Estimations

Although a better definition of capital items for dry tailings disposal is definitely required, based on lower bulking factors, capital costs might be perhaps 75% of those of conventional disposal methods.

14.5.3 Operating Costs

A more definitive tailings disposal operating strategy is still to

be worked out during pilot testing, but operating costs of perhaps 80% of those in current disposal technology seem indicated.

14.5.4 Major Economic Sensitivities

Annual operating costs are approximately 4 x as significant to the process economics as annual capital expenditures of the same dollar amount. This is due to the shielding effect of capital cost allowance and other write-offs, which lower the effective capital cost to about \$.25 per dollar for a oil sand plant owner.

14.6 Reclamation and Revegetation

The material geotechnical properties and the preferred disposal configuration lend themselves well to improved reclamation procedures at project termination. Repayment of the reclamation bond of \$.03/barrel of bitumen could be anticipated at project termination, by the Province to the operator, as "automatic" reclamation is integral to the chemical treatment approach.

14.6.1 Soil Amendments

Lower amounts of soil amendments seem indicated by revegetation work performed under a separate contract to A.E.R.T. The anticipated cost is lower than for current sand dyke amendment methods. It is possible no amendments will be needed; exact levels are still to be defined.

14.6.2 "Hydraulic" Seed Placement

The system may lend itself to a method by which seeds, fertilizer and amendments could be placed hydraulically in the upper most layer at project termination. The cost of such a method is at least an order of magnitude lower than current reclamation cost.

14.6.3 Sludge Reclamation

Dry tailings disposal completely eliminates the separate sludge fraction resulting in a relatively straight forward soil reclamation situation. It may also be capable of handling additional sludge from existing sludge ponds by co-depositing it with whole tailings.

14.6.4 Mine Backfill

Achieving the hindered settling effect with chemicals allows for an earlier and more efficient mine backfill operation.

14.7 Further Work

A great deal of additional laboratory and pilot plant scale work is needed to better refine, test and scale-up the process technology.

Recommendations for some of this work are made in Section 15.0.

15.0 RECOMMENDATIONS FOR FURTHER TESTING

There are many questions which need to be addressed before chemical treatment can be applied commercially to the disposal of oil sand tailings. Some of these questions may be at least partially answered by further laboratory tests, but most require larger scale continuous flow testing.

This section discusses the type of information needed and equipment and tests which would be proposed to improve confidence in the commercial potential of this process. The overall scope of further work required is presented in Table 15.1.

15.1 Continuous Pilot Scale Equipment Requirements

Figure 15.1 illustrates the major equipment items (and several alternative configurations) for testing of continuous flow chemical addition.

As can be seen from the figure, the major items which need to be tested for chemical addition are:

15.1.1 Chemical Injection Configuration

- a) To centrifugal pump casing for either lime slurry or polymer.
- b) Ahead of static in-line mixer.
- c) Ahead of motorized in-line mixer.

15.1.2 Lime Mixing Time

The floating roof mixer is intended to provide a means of varying the residence time while the material is being "mixed." (This would occur in-line over the considerable transportation distances involved in commercial oil sands operation.) As indicated, it is a low speed baffle plate type mixer rather than a "prop".

Our tests determined that propeller type mixers had a high tendency to entrain air, so even though we have a floating roof, we prefer to avoid this design. The baffle plate mixer provides an entirely different type of mixing with much lower shear forces.

15.1.3 Injection into Pump Casing

As far as we are aware, this is an unproven concept, but is at least attractive in principal. (It may be a patented design, also.) The great advantage is that the turbulence within the pump casing also provides the mixing energy. (The impeller tip speeds are usually very high causing considerable turbulence.) This principal might prove to have problems, especially with shearing

(15.2)

the polymer, but could also prove to be very attractive.

15.1.4 In-Line Mixers

Ideally, both lime and polymer could be added via static mixers, which are much cheaper and can even be more efficient in the right application. Our concerns are such things as the presence of "rocks" or glacial detritus in the oil sand which would tend to clog the stator, whether the pressure drop would be too high and whether additional mixing energy would be required. If the static mixer did not work and injection into a centrifugal pump casing did not work, then a motorized mixer would be used.

15.1.5 In-Line Motorized Mixer

This is the most expensive mixing option and, as such, would be our last resort. We would expect to be able to design such a mixer for any eventuality.

15.1.6 Lime Injection Configuration

The annular loop illustrated in Figure 15.1 might provide sufficient mixing via in-line blending to obviate any mixing concerns. It would be by far the cheapest and simplest way to perform the mixing operations. However, we have not assumed, at least for the early testing, that it could be used alone. Another configuration which could be used is a "bar" injector which is illustrated in Figure 15.2. If the loop arrangement does not work there may be an incentive to investigate such possibilities. It may prove particularly attractive for polymer/nutrient injection just prior to deposition.

15.1.7 Ca⁺⁺ Ion Specific Electrode

The best control strategy for lime (CaO) addition is probably the monitoring of excess solution Ca⁺⁺ by a calcium ion specific electrode. Although the housing design (to prevent bitumen contamination etc.) and the location of the electrode are concerns, it is expected these factors can be worked out in practice.

15.2 Design and Construction of Apparatus

Several months lead time will be required for design and construction of equipment such as a floating roof mixer, the chemical injection system and the Ca⁺⁺ ion specific electrode housing and support structure. As indicated in Table 15.1, design overlaps initial equipment purchases and so does construction, to a certain extent. Any items found to be long lead time on delivery in initial discussions with equipment vendors would be ordered to suit the overall project schedule. Among the items which may require considerable design and long delivery times:

1) Mixers

We have found previously that several of the mixers are potentially long delivery items. This needs to be investigated further.

2) Ca⁺⁺ Ion Specific Electrode Housing

A fritted glass membrane for solution exchange may have to be specially fabricated by a glass supplier. Figure 15.3 illustrates a configuration which might be used for housing the Ca⁺⁺ ion specific electrode. It is likely that such an electrode would be too sensitive to be exposed to a bitumen containing solution directly, for fear of being completely coated. The liquid within the enclosure must be representative of the bulk of the fluid surrounding it, but relatively free of bitumen globules and possibly even from abrasive particles in the slurry which might damage the electrode.

The exterior surface of the electrode housing could (hopefully) be kept clear of bitumen and solids by the abrasive action of the slurry, by periodically reversing the flow and by occasional flushing with a solvent which can fully dissolve bitumen but which is compatible with the electrode.

15.3 Disposal Simulation

One of the most critical reasons for pilot scale testing of a disposal system design is to gain confidence in the geotechnical characteristics through simulation of a continuous flow discharge to a significant size embankment. Many of the variables which were measured in the laboratory test programs such as angle of repose, as a function of discharge velocity, need to be rechecked on this scale of operation. Included in this test would be continuous in-line mixing of chemicals and an investigation of slurry and settled solids properties. In particular, we need to verify that a chemical addition of 450 ppm of calcium oxide and 4 ppm of polymer on average whole tailings (900 and 8mg/l on water only) is sufficient to give complete homogeneity of deposited solids.

In the flume simulation work, only one test was able to achieve the ideal result of deposition of the material at the in-situ density. It remains to be determined whether or not this particular result can be reproduced consistently. For example, the effect of variations in the fines and clay contents of different oil sands on the settled density of the treated whole tailings needs to be ascertained.

Experimentation with various heights of lifts and deposition over

(15.4)

various lengths of time is desirable. The effect of a small bulldozer for track-packing on material in various stages of drying and drainage should also be investigated. While it is difficult to design this type of experiment in a scientifically reproducible manner, observation by geotechnically competent specialists will provide a great deal of information about the design of larger scale structures. Test work on this scale may also provide a better indication of the drainability of the material under field conditions than is possible in the laboratory work conducted to date.

These larger scale disposal simulation tests will also provide an opportunity for significant scale revegetation experimentation with jack pine and slender wheat grass, analogous to the laboratory scale growth testing which has been conducted to date. It is hoped to deposit the upper layer of "soil" material simultaneously with fertilizer and soil amendments. Ideally, the upper surface of the tailings can be shown to sprout into life of their own accord several weeks after completion of the deposition experimentation.

15.4 Geotechnical Evaluation

The geotechnical test requirements would be very similar to those which were reported in Section 8.0. The previous laboratory test work will allow a narrower range of design conditions to determine properties such as drainage rates, drying rates, permeability, wet and dry densities and the angle of internal friction of the material deposited. The size and duration of such pilot scale test work may also allow a more comprehensive investigation of the extent to which carbonation increases the cohesion and shear strength of the deposited soil. (In previous tests this result was somewhat erratic.
.)

15.5 Chemistry and Mineralogy

Many of the chemical and mineralogical characteristics of the system are sufficiently uncertain that they cause considerable doubt in the projection of engineering design variables. As an example, the connate water composition for the extraction tar sand feed has significant effects on the tailings water quality and consumption of lime. In addition to the direct consumption of lime by carbonate entering the process water, an indirect consumption may occur due to the build up of salinity in the process water recycle and the necessity of a bleed stream to maintain the chloride level below that at which extraction efficiency is affected. Uncertainties as to the bicarbonate and salinity levels which will be encountered in oil sand connate water in future have influenced the accuracy of the projections. In turn, the accuracy of the economics as to the necessity of and the volume of recycle water and particularly the volume of the possible bleed water

stream are significant to the overall costs of the chemical treatment approach. This could prove to be a major cost factor.

A further investigation into the extent to which bicarbonate is created in the tumbler reject stream, secondary recovery and tailings pond portions of the process water stream is believed to be warranted. While the aggregate creation of bicarbonate due to the CO_2 adsorption into alkaline solutions may only amount to 30 to 40 ppm/yr, the huge volumes lead to an expense of several million dollars per year for additional lime to precipitate the bicarbonate produced. A number of similar concerns can be identified as having impacts of +10 million dollars per year in capital or operating expense. Such items should be investigated in order of declining cost.

Kaolinite and Illite are the two main clays to absorb significant amounts of calcium in the chemical treatment process. An investigation into the amount of kaolinite and illite which might be encountered in a commercial operation, their variability, and their adsorption characteristics is believed warranted. Specifically, the cation exchange capacity for calcium for each mineral and the additive, synergistic or antagonistic effects of the two minerals in the presence of calcium should be determined.

The relationship of calcium as determined by an ion specific electrode to various properties evidenced during coagulation and settling of lime treated tailings should be researched. While it is believed that a calcium ion specific electrode is the simplest means of monitoring the optimum additional level of lime, it is expected that the residual calcium concentration and solution after lime addition may be affected by the mixing, the contact time and a number of other variables. Because calcium specific ion electrodes are not normally used in slurries with significant bitumen contamination, some trial and error is anticipated for development of housings and support systems to protect the electrode from bitumen. The extent to which bitumen might interfere with the working of the calcium ion electrode or the reactions involving lime themselves also needs to be investigated.

All of the test work in Section 15.5 can be conducted on a laboratory scale rather than on a pilot plant scale. It could also be conducted during the design and construction phase for the pilot plant test work.

The complete pilot plant test work schedule should be revised once the design and construction of the pilot plant has been completed and careful analysis of the limitations of the pilot plant has been completed.

15.6 Water Treatment Pilot Tests

Water treatment may yet prove to be a potentially difficult and

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expensive aspect of the entire process. Work being done under UP-C-526 should define the technically and economically preferred method(s) of treating conventional oil sands tailings disposal waste water. Potentially the same treatment may work in this application or slight modifications may be required. If modifications are required they should be pilot tested to verify workability on-line.

15.7 Modify Material Balance Models

The "pond water material balance model" completed during this work also serves to model the water related aspects of the lime treatment process. This should be further modified to include solids handling so that the volume of both solids and water which have been deposited (and to some extent recovered, in the case of the water) is known accurately at any point in time. The current spread sheet "Report Manager" model may prove inappropriate for such programming and a Fortran type model may be required.

The biggest problem with the modelling so far, has been the lack of data necessary for proper accuracy. Assumptions have been made about extraction plant throughput, oil sand composition (i.e. connate water salinity and minerals) and many variables which affect the overall behaviour of the system. Where possible, actual Syncrude (or other lease data) should be used, rather than assumptions.

A narrowing of the design range of quality and quantity criteria and an improvement in the capital and operating cost accuracy should result from this work.

15.8 Revise Disposal System Designs

At present, there is insufficient data to discriminate between three possible disposal system designs. Larger scale data will improve confidence in many design factors and should help to provide a focus on which option(s) might be simplest and most economic. Trial dozer track-packing and experimentation with lift heights should help verify the hydraulic dyke construction procedure which will be required.

15.9 Revise Cost Estimates

A fairly comprehensive disposal system operating plan will be required to make an accurate estimate of operating costs. As operating costs have previously been found to be about 4x more significant to the overall project economics than capital costs, about 4x more detail is required for the operating plan for a comparable level of confidence in costs.

15.10 Revise Economic Model

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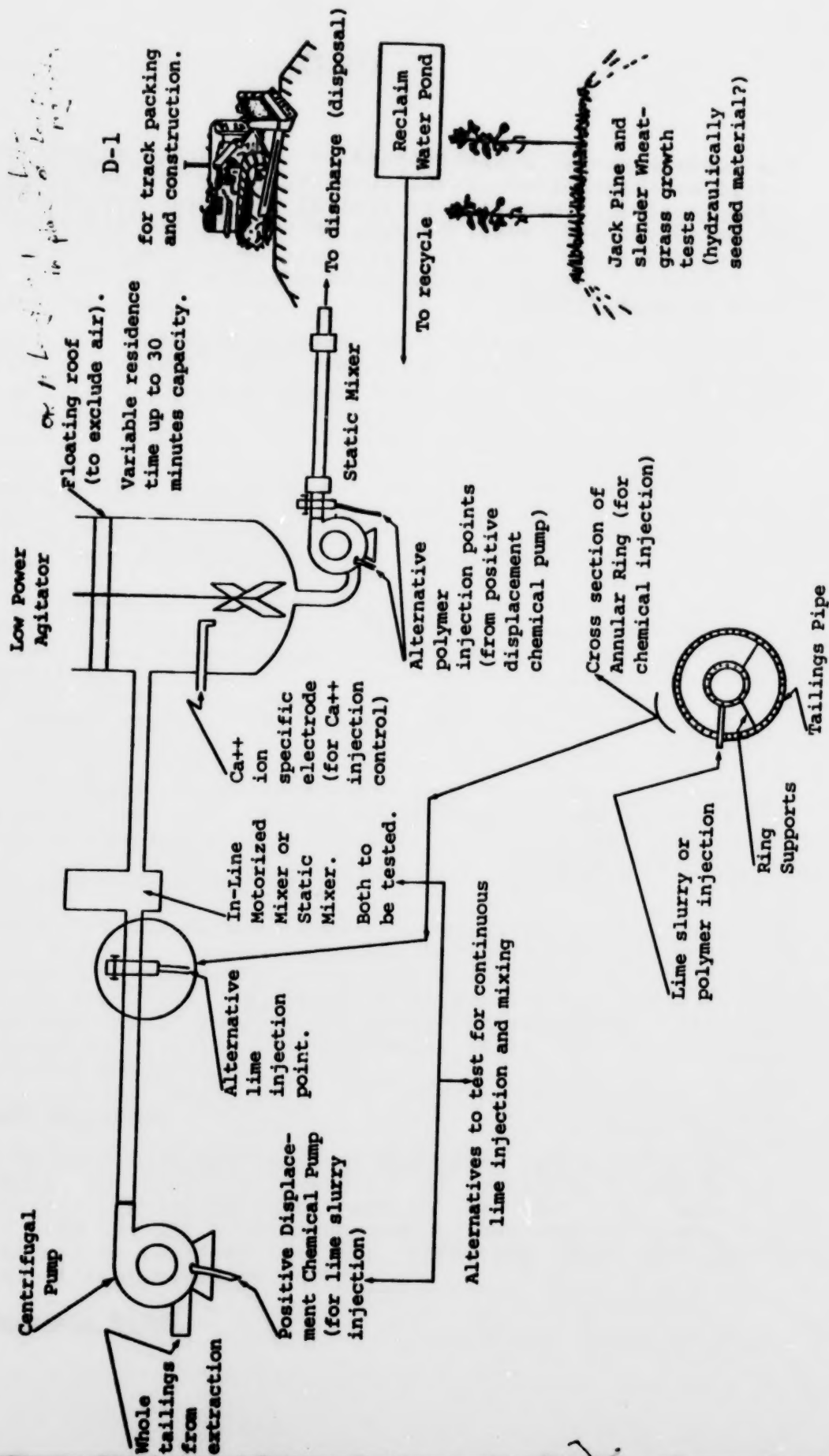
The model needs to be refined to incorporate a greater level of detail as information accumulates. By using the multipage feature, comprehensive information on capital equipment and operating costs can be developed with totals automatically transferred to a summary table.

15.11 Prepare Report

A comprehensive report will be prepared to present the accumulated data and also provide a format for feedback on estimates and assumptions.

Figure 1

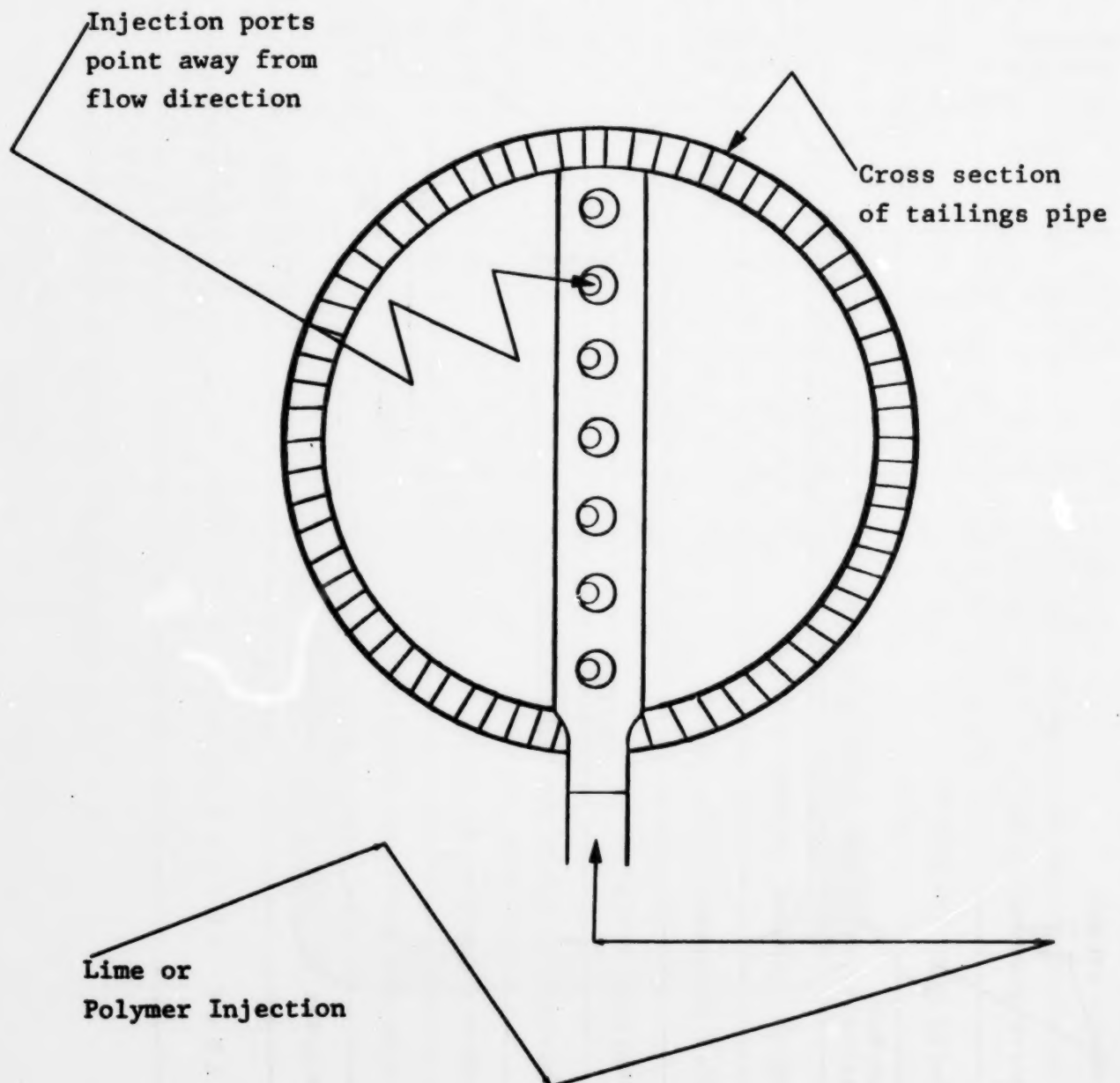
Schematic of Proposed T.P.H. Pilot Scale Test Alternatives



(15.9)

Figure 15.2

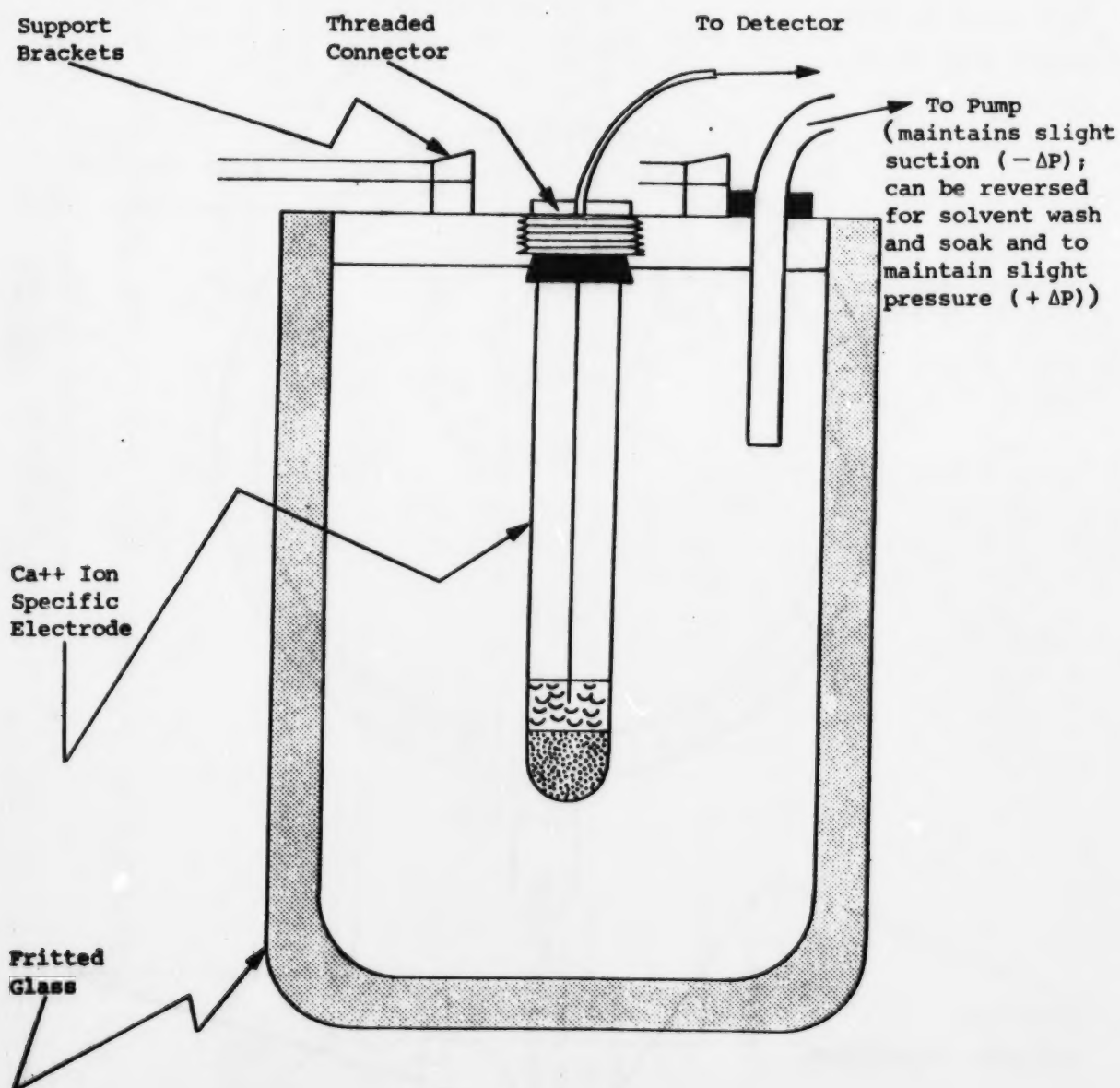
Alternative Chemical Injection System



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Figure 15.3

Ca⁺⁺ Ion Specific Electrode Housing



Recommended Schedule for Further Testing

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[illegible]